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MID- AND FAR-INFRARED *INFRARED SPACE OBSERVATORY* LIMITS ON DUST DISKS AROUND MILLISECOND PULSARS

T. Joseph W. Lazio and J. Fischer
Remote Sensing Division, Code 7213, Naval Research Laboratory, 4555 Overlook Avenue, SW, Washington, DC 20375-5351; Joseph.Lazio@nrl.navy.mil, Jacqueline.Fischer@nrl.navy.mil
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ABSTRACT

We report 60 and 90 μm observations of seven millisecond pulsars with the *Infrared Space Observatory*. The pulsar PSR B1257+12 is orbited by three planets, and other millisecond pulsars may be orbited by dust disks that represent planets that failed to form or their residue. We do not detect any infrared emission from the seven pulsars in our sample, and typical upper limits are 100 mJy. Using a simple model, we constrain the typical dust disk mass to be on the order of less than 100 $M_\oplus$, assuming that the heating of any putative dust disk would be coupled only weakly to the pulsar's emission. If the planets around PSR B1257+12 are composed largely of metals, our limits are probably an order of magnitude above plausible values for the disk mass in metals. Future observations with the *Spitzer Space Telescope* should be capable of probing into the range of disk masses that could plausibly give rise to planets.

Key words: infrared: stars — planetary systems: protoplanetary disks — pulsars: general

1. INTRODUCTION

The first extrasolar planets discovered were found around the millisecond pulsar PSR B1257+12 (Wolszczan & Frail 1992). The system consists of (at least) three planets: planet A with an approximately lunar mass, planet B with $M = 4.3 \pm 0.2\ M_\oplus$, and planet C with $M = 3.9 \pm 0.2\ M_\oplus$ (Konacki & Wolszczan 2003). Although planetary systems around main-sequence stars had been long anticipated and numerous such systems have been found since, pulsar planetary systems were unexpected. It was assumed that any planets orbiting the pulsar progenitor would have become gravitationally unbound in the supernova that produced the pulsar.

Various mechanisms have been proposed for the formation of these planets (Phinney & Hansen 1993; Miller & Hamilton 2001; Hansen 2002), but all generally rely on an accretion disk around the pulsar within which the planets form. Millisecond pulsars are a class of pulsars that, subsequent to their formation, undergo an episode of mass accretion from a companion (van den Heuvel 1995; Wijnands & van der Klis 1998). This process is thought to occur via an accretion disk, which transfers angular momentum to the pulsar as well, thereby spinning it up. Various mechanisms exist to shut down the accretion (e.g., evolution of the companion), but if the accretion is not 100% efficient, the millisecond pulsar will be left with an orbiting disk of material. Such a residual accretion disk is a natural location for the formation of planets. Even if planets form, the formation process may leave a debris disk. Gozdziewski et al. (2003) investigated the long-term stability of a debris disk in the PSR B1257+12 system, finding a stable zone outside 1 AU.

Since the discovery of planets around PSR B1257+12, a planet has also been found around the pulsar PSR B1620−26 (Backer et al. 1993; Thorsett et al. 1993, 1999; Rasio 1994; Joshi & Rasio 1997; Ford et al. 2000; Sigurdsson et al. 2003; Richer et al. 2003) in the globular cluster M4. In contrast to the planets orbiting PSR B1257+12, which are thought to have formed in situ, the planet orbiting PSR B1620−26 is thought to have been acquired during a dynamical exchange within the globular cluster.

Pulsar planetary systems offer valuable insights, even if their total number is unlikely ever to approach the number of planetary systems around main-sequence stars. Taken together the two pulsar planetary systems already indicate that planets can form and exist in a wide variety of environments. The presence of terrestrial-mass planets around PSR B1257+12 suggests that terrestrial planets may be widespread, a hypothesis to be tested by future space missions such as *Kepler* and the *Terrestrial Planet Finder*. Planets orbiting main-sequence stars near the Sun are found almost exclusively around stars with solar or supersolar metallicities (Gonzalez 1997; Santos et al. 2001), which has led to the belief that only stars with high metallicities can host planets. In contrast, the planet around PSR B1620−26, if it was acquired during a dynamical exchange, has probably existed for a substantial fraction of the age of the globular cluster M4. This is a low-metallicity globular cluster, suggesting that planets can form in low-metallicity environments.

Although the notion that planets can form in a residual accretion disk is plausible, no such examples of residual accretion disks are known. The presence of a planet (or stellar companion) can be inferred using traditional pulsar timing techniques from the periodic advance and delay of the arrival time of the pulsar's pulse, due to the pulsar's reflex motion. A relatively uniform disk of material would produce little reflex motion and therefore would remain undetected by these traditional techniques. Detecting dust disks around millisecond pulsars not only would elucidate the late stages of millisecond pulsar "spin up" and planet formation, but it also would be a new probe of the local environments around millisecond pulsars.

A modest number of unsuccessful searches for infrared emission from dust disks around millisecond pulsars have been conducted. Figure 1 summarizes the current situation, using PSR B1257+12 as an example. The limits for other pulsars are similar.

This paper reports 60 and 90 μm observations of seven pulsars with the ISOPHOT instrument on board the *Infrared Space Observatory* (*ISO*) satellite. In § 2 we describe the

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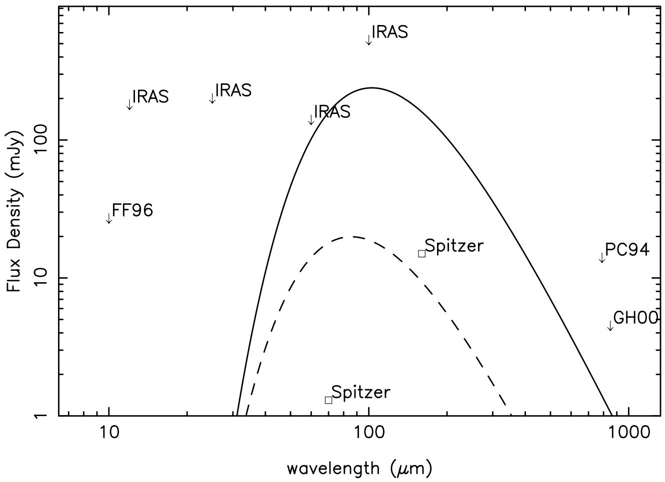

FIG. 1.—Summary of current limits on infrared dust emission from around millisecond pulsars, using PSR B1257+12 as an example. Shown are limits placed by 10 μm imaging by Foster & Fischer (1996; labeled FF96), *IRAS* limits determined by Foster & Fischer (1996; labeled IRAS), limits from 800 μm imaging by Phillips & Chandler (1994; labeled PC94), and limits from 850 μm imaging by Greaves & Holland (2000; labeled GH00). Also shown are the expected confusion limits for the future observations with the *Spitzer Space Telescope* at 70 and 160 μm. This pulsar was not observed as part of this *ISO* program. The solid curve shows the expected emission from a 300 $M_\oplus$ dust disk composed of dust particles 0.1 μm in size and heated by 1% of the spin-down luminosity of the pulsar, while the dashed curve shows the expected emission from a 10 $M_\oplus$ disk composed of 0.1 μm dust particles and heated by 0.1% of the spin-down luminosity (Foster & Fischer 1996). Upper limits on infrared emission for other millisecond pulsars are similar.

observations and present our results, and in § 3 we describe how our results constrain the presence of dust disks around millisecond pulsars and present our conclusions.

2. OBSERVATIONS AND DATA ANALYSIS

We compiled a list of millisecond pulsars known prior to 1994 August with distances less than 1 kpc. Distances are estimated from the Taylor & Cordes (1993) model and should be accurate to approximately 25%. Most of these millisecond pulsars lie at high Galactic latitudes.

Of these, seven were observed with the ISOPHOT instrument (Lemke et al. 1996) on board the *ISO* satellite (Kessler et al. 1996) between 1996 August and 1997 May. Table 1 summarizes the observational details; we also report the distance to each pulsar and, anticipating later discussion, whether or not it is a binary and its spin-down luminosity.[1] All of the observations used the P32 observing mode with the C100 detector. In this mode the spacecraft was commanded to cover a series of raster pointings around the nominal pulsar position. At each raster pointing an internal chopper pointed the beam toward 13 adjacent sky positions. The throw of the chopper was larger than the offset between raster pointings. The result was that, in general, an individual sky position within the raster was observed multiple times or oversampled. Before and after each observation of a pulsar, an internal calibration source was observed.

The analysis of the pulsar observations largely followed the standard ISOPHOT analysis pipeline. The key difference was the amount of ‘‘deglitching’’ performed. Glitches result from cosmic rays striking the detector or secondary electrons produced by spacecraft materials struck by primary cosmic rays. Failure to remove glitches can corrupt later calibration of *all* data, not just of the portion containing the glitches. The standard ISOPHOT analysis pipeline removes glitches but does so without making use of the redundancy implicit in the oversampled P32 observations.

Deglitching proceeded in the following fashion. Within each spacecraft pointing the chopper would sweep past a particular sky position multiple times (typically 3–5 times). For each sky position, the median signal level was determined and then subtracted from all observations at that sky position. The observations from all sky positions were then combined to form a signal strength histogram. A signal strength threshold was specified, and signals above this level were eliminated. Typically 3%–10% of the signals were eliminated in this stage. Depending upon the number of chopper sweeps per spacecraft pointing and deglitching prior to this stage, the median signal strength per sky position could not always be determined accurately. Thus, additional manual deglitching was done to remove any remaining outlying signals. Our use of the observations of the internal calibration sources followed the standard ISOPHOT analysis pipeline.

After deglitching and calibration using the internal calibration sources, mapping was done within the ISOPHOT Interactive Analysis package. Measurements from the individual detector pixels were co-added to form a sky image, with the contributions from the individual detector pixels weighted by their distances from the image pixels. Doing so takes into account the beam profile falling on each detector pixel. We also employed a median flat field, which has the effect of substantially reducing our sensitivity to any extended emission in the field. As we are attempting to detect point sources, we regard this reduced sensitivity to extended emission as unimportant.

In no case have we identified a source at the location of a pulsar. Utilizing the inner quarter of the image, we determined the rms noise level. We take our upper limits to be 3 times this rms noise level. Table 2 summarizes the upper limits.

3. DISCUSSION AND CONCLUSIONS

We have not detected infrared emission associated with any of the pulsars observed with *ISO*. Other infrared and submillimeter observations of millisecond pulsars have been conducted, and all of these have yielded only upper limits as well. Those observations most relevant to our sample of millisecond pulsars are those by Foster & Fischer (1996) at 10 μm and Greaves & Holland (2000) at 850 μm. Foster & Fischer (1996) also utilized *IRAS* observations to obtain upper limits on the infrared emission from their sample of pulsars. As Figure 1 shows, the upper limits set by *IRAS* are typically well above the limits set by our *ISO* observations. Moreover, there is unfortunately little overlap between these three samples of pulsars (those whose observations are reported here, Foster & Fischer 1996, and Greaves & Holland 2000). Most of the pulsars that have been observed between 10 and 850 μm have been observed at only one or two wavelengths.

Foster & Fischer (1996) developed a model for the infrared emission from a dust disk around a millisecond pulsar. Their model assumes that the disk consists of particles of a uniform radius a heated by a fraction $f_{\rm sd}$ of the pulsar's spin-down luminosity $L_{\rm sd}$. The total mass of the disk is m_d. While the model is simplistic—an actual dust disk presumably consists of particles with a range of sizes, the heating mechanism is left

[1] The spin-down luminosity of a pulsar is a measure of its energy loss due to magnetic dipole radiation and is given by $L = I\Omega\dot{\Omega}$, where I is its moment of inertia and Ω is its rotation frequency.

TABLE 1
PULSARS OBSERVED

Name	Binary?	Distance (kpc)	Spin-down Luminosity ($L_\odot$)	Wavelength (μm)	P32 Raster	On-Source Time (s)
PSR J0034−0534	Y	0.98	10	90	3 × 8	1402
PSR J1640+2224	Y	1.19	0.88	60	3 × 6	1012
	...	...	...	90	3 × 8	848
PSR J1730−2304	...	0.51	<0.35	60	3 × 6	1590
	...	...	...	90	3 × 8	1232
PSR B1855+09	Y	0.91	1.1	60	3 × 6	1012
PSR J2124−3358	...	0.25	1.7	60	3 × 6	1012
	...	...	...	90	3 × 8	848
PSR J2145−0750	Y	0.50	<0.048	60	3 × 6	1590
	...	...	...	90	3 × 8	848
PSR J2322+2057	...	0.78	0.62	60	3 × 6	1804
	...	...	...	90	3 × 8	1402

unspecified, nonequilibrium effects such as stochastic heating are ignored, and the impact of any stellar companions (see Table 1) on the disk are ignored—we believe that this simplicity is justified, given the uncertainties of the heating mechanism and of the environs of a millisecond pulsar.

In this model, for $f_{sd} \sim 1\%$, typical dust temperatures are predicted to be $T \approx 10-50$ K for disks having $m_d \sim 100\ M_\oplus$ and $a \sim 1\ \mu$m and being heated by a pulsar with $L_{sd} \sim 1\ L_\odot$. These temperatures are similar to the lower temperature range used by Koch-Miramond et al. (2002) and are considerably lower than those assumed ($\approx$150 K) by Phillips & Chandler (1994), who estimated disk temperatures by scaling from observations of T Tauri stars. The lower temperatures result from our assumption of a weaker coupling between the pulsar's spin-down luminosity and the disk. Phillips & Chandler (1994) considered disk temperature to be a major uncertainty in converting from measured flux densities to inferred disk masses. Accordingly, our assumption of a weaker coupling means that larger disk masses can be tolerated without violating the observational constraints.

Given the paucity of data, it is not possible, in general, to constrain all three parameters of this model with the existing observations. We therefore adopt an approach in which we infer limits on two parameters of the Foster & Fischer (1996) model for fiducial values of the third parameter. Here, as an example, we consider the millisecond pulsar PSR J0034−0534 (Bailes et al. 1994), which has a probable white dwarf companion, is at a distance of 1 kpc, and has a spin-down luminosity of 10 $L_\odot$. Greaves & Holland (2000) placed a 2 σ limit of 3.7 mJy at 850 μm, and we place a 2 σ limit of 50 mJy at 90 μm. Figure 2 shows the allowed region of the disk mass–grain size plane given these observational limits and an assumed heating efficiency of $f_{sd} = 1\%$.

Allowed regions in the m_d-a plane occur for one of two possible reasons. First, the peak of the dust disk emission may appear shortward of 90 μm, where no constraints exist for this pulsar, with the Rayleigh-Jeans tail of the emission falling below the two measured values. This region is to the lower left in Figure 2. Second, the peak of the emission may appear between 90 and 850 μm, but with a magnitude comparable to that measured at 90 μm so that the Rayleigh-Jeans tail again does not violate the 850 μm limit while the Wien tail of the emission does not violate the 90 μm limit. This region is to the lower right in Figure 2. Obviously, a lower value of f_{sd} would

TABLE 2
DUST DISK IR EMISSION UPPER LIMITS

Name	Flux Density (mJy)
60 μm	
PSR J1640+2224	80
PSR J1730−2304	35
PSR B1855+09	190
PSR J2124−3358	100
PSR J2145−0750	100
PSR J2322+2057	59
90 μm	
PSR J0034−0534	48
PSR J1640+2224	59
PSR J1730−2304	140
PSR J2124−3358	55
PSR J2145−0750	73
PSR J2322+2057	39

NOTE.—Upper limits are 3 σ.

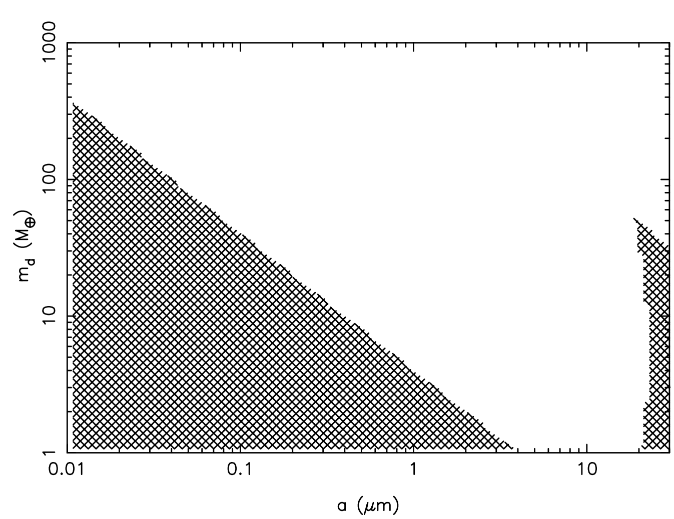

FIG. 2.—Allowed disk masses and grain sizes for a dust disk orbiting PSR J0034−0534. The crosshatched region indicates disk masses and grain sizes that do not violate the observational limits at 90 and 850 μm. A heating efficiency of $f_{sd} = 1\%$ has been assumed.

produce larger allowed regions in the m_d-a plane. Larger allowed regions would also exist for other pulsars (Table 1) with smaller spin-down luminosities.

We conclude that, with the current observational constraints and the assumption of a fairly weak energy coupling betwe pulsars and disks, dust disks on the order of 100 $M_\oplus$ could easily exist around millisecond pulsars. Koch-Miramond et al. (2002) have reached similar conclusions based on 15 and 90 μm observations. To the extent that such disks would be uniform, they would also escape detection from traditional pulsar timing techniques. Pulsar timing techniques utilize the advance or delay of the pulse arrival time resulting from the pulsar's reflex motion to detect planetary or stellar companions. A relatively uniform dust disk would produce little reflex motion.[2]

The current limits on dust disk masses are far larger than the mass of the disk thought to have produced the planets around PSR B1257+12. The minimum combined mass of the two larger planets in that system is 8.2 $M_\oplus$ (Konacki & Wolszczan 2003). Assuming that these planets are mostly composed of metals, we expect that any dust mass prior to the planets' formation would be comparable in magnitude. Indeed, Hansen (2002) has shown how an initial disk of mass 0.1–10^{-3} $M_\odot$ containing on the order of 10 $M_\oplus$ in metals could form a system similar to that orbiting PSR B1257+12. (See also Miller & Hamilton 2001 and Fig. 1.) For those pulsars orbited by stellar companions, the companions will introduce regions of limited orbital stability within the disks, potentially implying even smaller expected disk masses. We conclude that current observational limits on dust disk masses are at least an order of magnitude above plausible values.

The mid- to far-infrared detectors (24, 70, and 160 μm) on the *Spitzer Space Telescope* should have sensitivities some 1–2 orders of magnitude better than the limits we report here. At a minimum, we expect that future observations with *Spitzer* may require more sophisticated modeling of disks, including the possible effects of stellar companions. If future observations with *Spitzer* do not detect infrared emission from dust disks around millisecond pulsars, the resulting mass limits should be in the range of 10 $M_\oplus$, sufficient to begin placing stringent constraints on their existence, or else the temperatures of any pulsar dust disks must be no more than a few kelvins.

[2] One possible exception to this conclusion would be a dust disk illuminated directly by the pulsar's beam. In this case the relativistic particle flow from the pulsar beam potentially could ionize portions of the disk and induce plasma propagation delays that might be detectable.

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