# The Census of Warm Debris Disks in the Solar Neighborhood from *WISE* and *Hipparcos*

Rahul I. Patel

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Rahul Indrakant Patel

We, the dissertation committee for the above candidate for the

Doctor of Philosophy degree, hereby recommend

acceptance of this dissertation

**Stanimir Metchev - Dissertation Advisor**
**Adjunct Professor, Department of Physics and Astronomy**

**Michael Zingale - Chairperson of Defense**
**Associate Professor, Department of Physics and Astronomy**

**Matthew Dawber - Committee Member**
**Associate Professor, Department of Physics and Astronomy**

**Rebecca Oppenheimer - External Member**
**Curator, Professor, and Chair, American Museum of Natural History**

This dissertation is accepted by the Graduate School

Charles Taber
Dean of the Graduate School

Abstract of the Dissertation

# The Census of Warm Debris Disks in the Solar Neighborhood from *WISE* and *Hipparcos*

by

**Rahul Indrakant Patel**

**Doctor of Philosophy**

in

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Debris disks are optically thin circumstellar disks around main-sequence stars, comprised of micron-sized grains. The dust is generated from destructive collisions of planetesimals, induced from gravitational perturbations by large planets. Debris disks can act as signposts for planetary systems, through which, a universal picture can be obtained that encompasses the evolution and architecture of the Solar System's own dust disk and planetary system. The dust in these disks can be detected by their thermal infrared flux, measured as an excess above the photospheric emission. Dust at different circumstellar locations, inferred from the peak wavelength of the detected emission, can act as a probe for local dynamical activity in the system. Over the last thirty years, cold disks, analogous to the Kuiper Belt, have constituted the bulk of debris disk detections. Warm disks, analogous to the Main Asteroid belt, can act as signposts for dynamical activity in the terrestrial planet

zone, but are rare in contrast. The Wide-Field Infrared Survey Explorer (*WISE*) space telescope mapped the entire sky in two near-IR and two mid-IR bands in 2012. The two mid-IR bands are well placed to probe dust emission in the terrestrial planet zone of these stars, at sensitivities greater than the last all-sky IR survey in 1983. *WISE* also provides us for the first time an opportunity to contemporaneously measure the photospheric and IR excess wavelengths of the entire sky, increasing sensitivity to fainter levels of dust.

In this thesis, I present an unbiased survey of warm disks around main-sequence Hipparcos stars in the solar neighborhood, detected using data from the *WISE* All-Sky Database. Our series of surveys builds upon each other to find previously undetected faint, warm debris disks by including bright photometrically saturated stars in *WISE*, using empirical photospheric colors, removing several non-trivial false-positive sources, and verifying and validating these detected excesses. This thesis adds a substantial number of new disk targets to the census of debris disks, as well as an assessment of the incidence rate of *WISE* disks in the solar neighborhood. The number and rate of detections can ultimately aid in enhancing our understanding of the formation and evolution of planetary systems.

To my family.

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# Acknowledgements

*Deshi Basara Basara, Deshi Basara Basara.*
— *The Dark Knight Rises.*

I have determined that I would rather write five more theses than another sentence in the acknowledgements. It has taken me much longer to finish this section — which I started after defending — than to write the entirety of Chapter 5. This is not because I don't want to get sentimental or that I have too many people to thank, though both are true. It's because writing the words "supportive" and "thankful" became repetitive and I started perusing the thesaurus too often. However, I then remembered that Mike Simon once said that "if a fifty cent word works, then don't use a fifty dollar one." So, what you will read here are plain words of the gratitude I feel toward all those who have shared in my triumphs and tribulations these past few years.

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# Chapter 1

# Introduction

## 1.1 Solar System Context

Since the discovery of the first extrasolar planets (exoplanets) around a main-sequence star, (HD 114762 b and 51 Pegasi b, Latham et al., 1989; Mayor & Queloz, 1995, respectively), a revolution has occurred in our understanding of planetary formation and evolution. We have seen exoplanets of a variety of flavors: gas giants at fractions of an astronomical unit (AU) from their star, binary planetary systems and even compact multi-planet systems. Giant planets are found with eccentricities ranging from 0–0.9, with sometimes large mutual inclinations. And roughly 50% of solar type stars have a chance of hosting a compact multi-planet system with periods shorter than a year (see review by Winn & Fabrycky, 2015).

In contrast, the planets in our Solar System follow nearly circular, low inclination orbits at distances such that terrestrial and gas giants are separated by the snow-line (see § 1.2.2). Since this Solar System is the only one we know of where a planet can sustain life, perhaps the key to finding another is to search for systems with similar architecture. Of course there are a few exoplanetary systems that may seem architecturally similar to our own. The HR 8799 multi-planet system is an excellent example, where the system's four gas giant planets are at the same equilibrium temperature as our gas giants are to our Sun (Marois et al., 2010).

But this is one in a multitude of over a thousand planets we have uncovered. And if the majority of planets we are finding do not resemble the architecture of the Solar System, we have to ask: Is the existence of another habitable planet likely? If so, how can we identify a system whose interplanetary environment would increase the habitability of an Earth analog?

Over the last thirty years, we have seen that exoplanetary systems can also

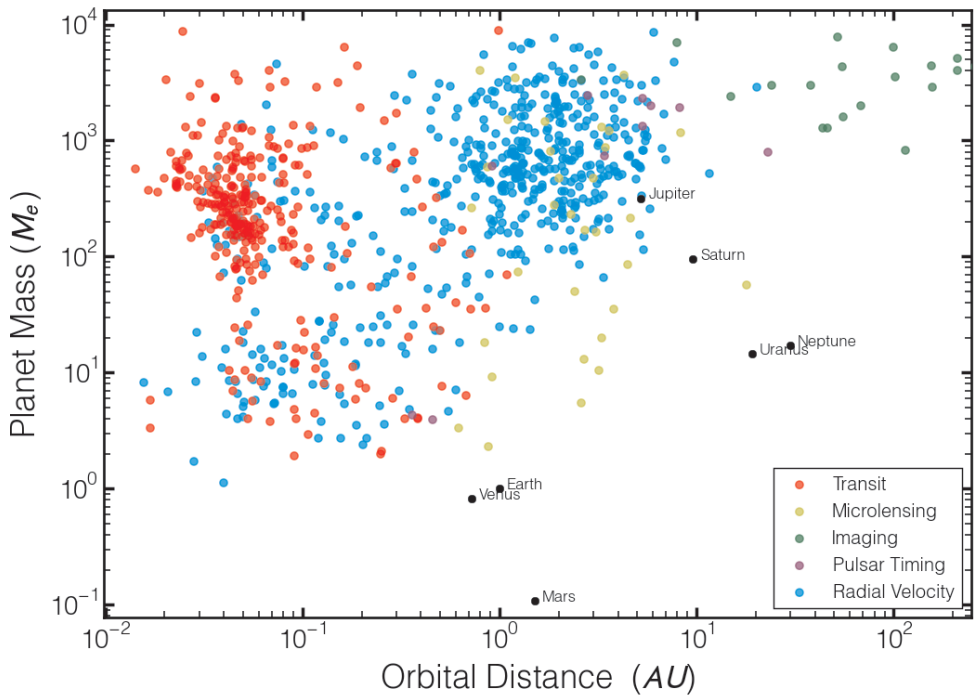


**Figure 1.1:** Distribution of exoplanet masses vs. their estimated orbital distance and color coded based on the technique used to detect them. This plot only shows exoplanets detected as of June 2015. Only planets with catalogued masses and orbital distances were plotted. $M\sin(i)$ values were used when exact values for the planet mass were unavailable. Solar System data is also plotted. Data was downloaded from `http://exoplanetarchive.ipac.caltech.edu/`. Credit: R. Patel.

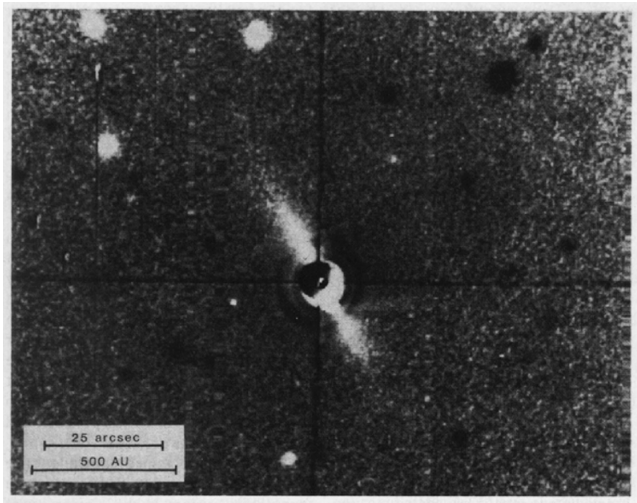


**Figure 1.2:** Resolved disk emission around the $\beta$ Pictoris star. First ever resolved image of a debris disk. The image was taken using a coronagraph at the Las Campanas observatory in Chile. The disk is edge-on and composed of solid particles. The flattened shape, rather than a spherical shell of particles is circumstantial evidence of planet formation. The circular shape in the center is due to the coronagraph and imperfect subtraction of the standard star. Image credit: Smith & Terrile (1984). Reprinted with permission from AAAS.

be identified by the presence of any dusty disks orbiting a main-sequence star. The first unresolved detection of extrasolar debris disks was by the *Infrared Astronomical Satellite* (*IRAS*) in 1983 of the Vega debris disk (Aumann et al., 1984). Further evidence from resolved images was taken by Smith & Terrile (1984) of the debris disk around the $\beta$ Pictoris system and galvanized the idea of these disks, which are created from the collisional grinding of planetesimals, are stirred by large planets (see Figure 1.2). Given that evidence exists that our own Solar System is a result of the concurrent evolution of our circumsolar disk and planets, then perhaps similarities can be drawn between what our circumsolar disk looked like at different stages in its evolution and the extrasolar debris disks astronomers have detected over the last thirty years. Another way to investigate this is to ask: is the likelihood of a system like ours — and hence the possibility of life — linked with the evolution of the disk and planets as a whole?

This thesis takes a step toward investigating these questions by identifying additional systems which have previously been overlooked and may hold a wealth of information with which to place our Solar System in context.

## 1.2 The Solar System's Debris Disk

### 1.2.1 Current Configuration

The eight planets in the Solar System follow a relatively ordered configuration. With the exception of Mercury, the orbits are close to circular, and are closely inclined to the invariable plane, where inclination angles range from 0.33°–2.19°. The four rocky planets are located interior to 1.7 AU, while the four gas giant planets are located beyond the snow-line — the point in relation to the Sun beyond which volatile molecules (e.g., $H_2O, CH_4$) condense — and all the way out to 30 AU.

The inner and outer planets are also segregated by a disk of material known as the Main Asteroid Belt (MAB). Located between the orbits of Mars and Jupiter, the MAB is composed of over a million kilometer-sized objects that can be metallic, stony or even carbon rich in composition.

It has been estimated that the mass of the MAB is $\sim 0.04 M_{\rm moon}$, but was much larger in the early Solar System (see § 1.2.2). Beyond the orbit of Neptune lies a large reservoir or minor planets composed of icy, volatile, cometary material with sizes greater than 1 km. These minor bodies, distributed in a thin belt the width of 20 AU, are known as the Edgeworth-Kuiper Belt (EKB).

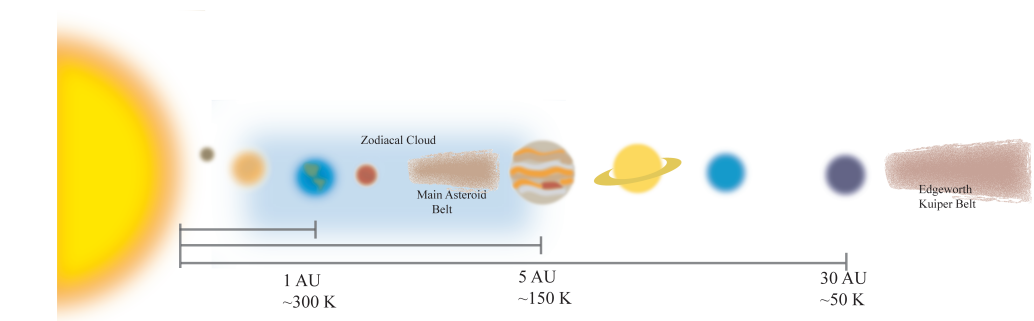


**Figure 1.3:** An illustration of the Solar System's planets, and major dust belts. Rough equilibrium temperatures are indicated at distances from Earth, Jupiter, and the inner edge of the EKB. The vertical positions of the planets relative to the Earth-Sun plane indicate rough inclinations. Distances and sizes are not to scale. Image credit: R. Patel.

In addition to the rings of large rocky bodies, a population of 10–100$\mu$m sized cometary and silicate grains inhabits the Solar System. This disk, known as the Zodiacal Cloud, has been seen in scattered light observations (Hahn et al., 2002), thermal emission from the Planck (Maris et al., 2006; Planck Collaboration et al., 2014), COBE (Kelsall et al., 1998), and the *IRAS* (Sykes,

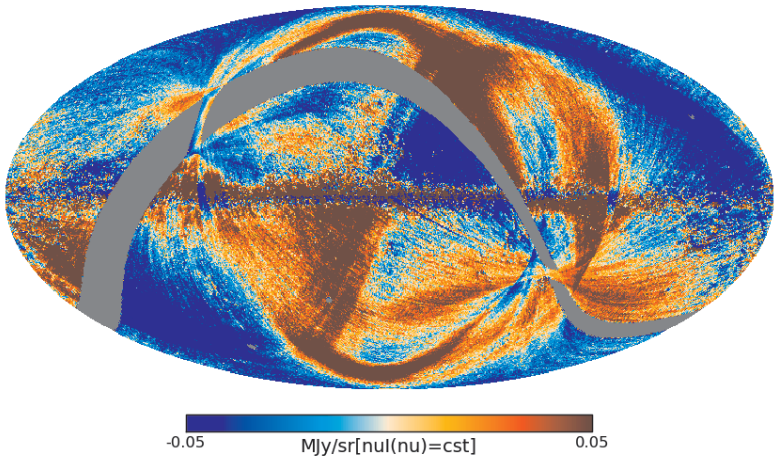


**Figure 1.4:** Galactic coordinate projection of the sky in the 850 GHz band from the Planck Satellite. The Zodiacal light emission is seen passing diagonally from the lower left to the top right, crossing the middle of the galactic plane. The top and bottom arcs are due to instrumental far side lobes. Image credit: (Planck Collaboration et al., 2014).

**Figure 1.5:** A faint glow seen along the ecliptic reveals the presence of 100$\mu$m sized grains that comprise the Zodiacal Light. Image credit to the European Southern Observatory. Image was taken at Cerro Paranal, Chile `http://www.eso.org/public/unitedkingdom/images/zodiacal-light/`

1990) missions, as well as inferred from spacecraft impact experiments. From the ground, the Zodiacal Cloud can be seen only on the darkest of nights, as a faint glow along the ecliptic (see Figure 1.5). The inner Zodiacal Cloud extends from the orbit of Venus all the way out to Jupiter. From most recent studies, it is thought that mm–cm sized grains are ejected from Jupiter Family Comets (JFC) as they approach the large tidal forces of Jupiter's gravity. The smaller sub-mm sized grains, which comprise the disk are thought to be created from the grinding down of the larger mm–cm sized ejected grains. The overall mass of the inner Zodiacal Cloud has been estimated to be $\sim 1-2\times10^{19}$ g (Nesvorný et al., 2010). The Zodiacal Cloud's density is so low that the overall disk brightness, when compared to the total emission of the Sun at all wavelengths (bolometric luminosity) is $L_{\rm ZODY}/L_{\odot} \sim 2 \times 10^{-7}$ (Nesvorný et al., 2010).

### 1.2.2 Dynamical Evolution Of Our Planetary System

The combined evolution of the planets, asteroidal and cometary disks are responsible for the current state of the Solar System. It is generally accepted that all the planets formed within the first 100 Myr (upper limit based on the final accretion time to create Earth; Allègre et al., 2008), after the Sun reached its place on the main-sequence. During this time, it has been hypothesized that the planets were in a compact configuration, all of them residing within 15 AU of the Sun (Batygin & Brown, 2010). Roughly 4.0–3.7 Gyr ago, scattering of the planetesimal populations that lay outside the orbit of Neptune at 15 AU resulted in angular momentum exchange between the gas giants and the disk. This led to a period of instability in which Jupiter and Saturn's orbits diverged, and eventually crossed their mutual 1:2 mean motion resonance. From this, Jupiter migrated inward by $< 0.5$ AU (Morbidelli et al., 2010), and pushed Saturn, Uranus and Neptune further out into the Solar System (Tsiganis et al., 2005).

This migration led to a period known as the Late Heavy Bombardment (LHB). During this time, Jupiter's short migration would have depleted the MAB by a factor of 10, while 97% of the EKB was probably removed as a result of Neptune's outward migration. The scattered comets and asteroids during this period are most likely responsible for the Lunar craters we see today (Gomes et al., 2005). It is also thought that a fraction of Earth's water supply was transported during the LHB either from the EKB or from water rich asteroids. In addition, the depletion of the MAB by Jupiter has implications for the emergence of life on Earth, as a massive MAB today might have resulted in a higher frequency of Terrestrial impacts. In essence, we would like to investigate the relationships a planetary system may have with its environment, similar to the evolution due to dynamical friction in our planet-disk

system, around other star systems.

## 1.3 Circumstellar Disk Evolution

Understanding the physical nature and processes governing the evolution of circumstellar disks is important if we are to understand the similarities between other systems and our own disk throughout its lifetime. In this section, I briefly outline the properties and characteristics of young gas-rich protoplanetary disks and their evolution into a dusty debris disk.

### 1.3.1 Protoplanetary Disk Evolution

The paradigm of planet formation begins with a nascent protoplanetary disk (PPD), composed of primordial gas and dust that remains post-star formation. The primordial material forms into a circumstellar disk, as a consequence of angular momentum conservation. The final radial extent of the disk is heavily sensitive to the angular rotation of the central star ($\Omega^2$) and even more sensitive to the infall time of the primordial material ($t^3_{\rm infall}$; Terebey et al., 1984). It is well accepted that 90–99% of a PPD is composed of gas, while the rest is made of micron to millimeter sized-dust grains.

The bulk of the gas is comprised of neutral $H_2$. Though difficult to measure, mid-IR rotational lines have been observed from hot ($> 600$ K) $H_2$ from the ground in systems like AB Aurigae (Bitner et al., 2007). Typically, however, tracers such as CO, and HCN line emissions are observed at sub-mm wavelengths to detect the gas in PPDs (e.g., for stars in young associations such as Ophiuchus and Taurus-Auriga, Andre & Montmerle, 1994; Beckwith et al., 1990, respectively). These observations have shown that the size of these disks can range from 10–100 AU, with masses $>0.005\ M_\odot$ (Osterloh & Beckwith, 1995). Dust masses are typically derived from dust thermal emission at mm-wavelengths, which probe the large grain population. The masses are typically derived by assuming an upper limit to the grain size (usually around mm sizes) and some assumed opacity values (Beckwith et al., 1990). Figure 1.6 shows the masses of observed PPDs (ages $< 10$ Myr), indicating disk masses on the order of a few hundred $M_{\rm earth}$.

The majority of the primordial gas and dust dissipates within the first $\sim$10 Myr. Viscous accretion of gas and dust onto the star has been attributed to the clearing of the inner regions (a few AU) of the star, which is supported by a lack of near-IR flux (2–5$\mu$m) and the presence of forbidden line accretion signatures (e.g., OI, SII; Hartigan et al., 1995). Photoevaporation from the central star will also carve out the outer disk. In this process, high-energy UV