Mem. S.A.It. Vol. 83, 490

Memorie della

Dust in white dwarfs and cataclysmic variables

(An observational perspective)

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Abstract. Recent infrared observations, particularly from the *Spitzer Space Telescope*, of white dwarfs, cataclysmic variables and other interacting compact binaries, have revealed the presence of dust in many systems. I review the discovery, properties, and implications of dust around white dwarfs and cataclysmic variables.

Key words. binaries: close – Stars: dwarf novae – novae, cataclysmic variables – dust, extinction – Infrared: stars

1. Introduction

Dust disks are a common presence in a wide variety of astrophysical situations, ranging from young stars to central engines of quasars and, closer to home, the recently discovered largest ring of the planet Saturn. The first dust disk around a white dwarf (WD), G29-38, was discovered in 1987 via its infrared (IR) excess over the WD photosphere (Zuckerman & Becklin 1987), although it took another decade to cast aside lingering doubts that the IR excess was truly due to dust and not an unresolved brown dwarf companion (Koester et al. 1997; Kuchner et al. 1998). In 2003, Jura (2003) developed a model for the origin of WD dust disks involving the tidal disruption of a comet or asteroid that was perturbed into the WD Roche lobe, likely due to the gravitational influence of a remnant planetary system.

It wasn't until 2005 that the second dusty WD, GD 362, was discovered (Becklin et al. 2005; Kilic et al. 2005). At the end of 2010, 20 dusty WDs were known (see Table 5.1 in Farihi 2011), largely owing to sensitive IR observations obtained with the *Spitzer Space Telescope* (e.g., see Figure 1). Recently, the *WISE* IR Excesses around Degenerates (WIRED) Survey (Debes et al. 2011), which cross-correlated the Sloan Digital Sky Survey Data Release 7 preliminary WD Catalog (Kleinman 2010) with the *Wide-Field Infrared Survey Explorer* all-sky photometry at 3.4, 4.6, 12, and 22 μm, has nearly tripled the number of known dusty WDs (see Figure 2). These objects are unique laboratories for studying the late evolutionary stages of planetary systems, and provide insight into the future of the Solar System (and, by extension, the future of all planetary systems around current main sequence stars).

2. The metal-rich white dwarf–dust connection

Predating the discovery of dust around WDs, it was known that a small fraction of WDs show absorption lines of metals in their optical and

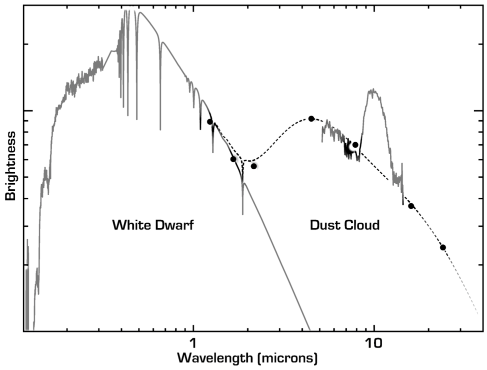

Fig. 1. UV spectrum of the archetype dusty WD, G29-38, from the *International Ultraviolet Explorer*, with an optical–near-IR model WD spectrum, and IR photometric and spectroscopic data from *Spitzer*, along with a model (dotted line) consisting of the WD model spectrum and a blackbody dust cloud. The spectrum from *Spitzer*'s Infrared Spectrograph (IRS) shows a prominent 10 μm emission feature attributed to amorphous silicate dust grains. Image courtesy of NASA/JPL-Caltech/M. Kuchner (GSFC); also see Reach et al. (2005).

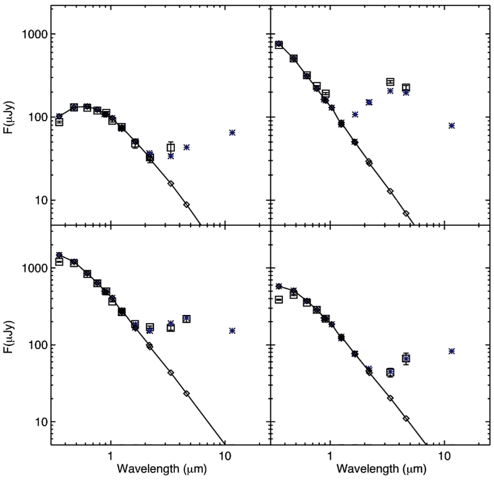

Fig. 2. Examples of newly discovered WDs with IR excess indicative of dust disks, from the WIRED Survey. Photometry from SDSS, 2MASS and/or UKIDSS, and *WISE* is shown as squares, the solid line and diamonds are a WD model, and the asterisks are a combined model fit to the WD+dust disk.

UV photospheric spectra (e.g., Lacombe et al. 1983; Shipman & Greenstein 1983; Zeidler-K.T. et al. 1986). Gravitational settling times in hydrogen-rich (DA) WD atmospheres are very short (a few days to $\lesssim$1000 yr), so metals will quickly diffuse out of the photosphere. Thus, the observed metals were thought to be supplied by ongoing accretion from the interstellar medium (ISM) (Sion et al. 1990). This explanation was problematic for a number of reasons; notably, explaining the relative elemental abundances of the accreted material, which do not match equilibrium ISM values (see Section 5.6.6 in Farihi 2011).

It is a testament to the strength of the asteroid disruption model for WD dust disks that it also explains the observed metal-rich WDs, via accretion from circumstellar dust. Reach et al. (2005) showed that the 10 μm silicate emission feature in the dusty WD G29-38 is most similar to that of the zodiacal light in the Solar System (i.e., sunlight scattered from dust originating from depleted comets and asteroid collisions). Zuckerman et al. (2007) showed that the relative abundances of accreted metals in the dusty WD GD 362 closely match those of terrestrial planets (specifically, Earth, Moon, Mars), pointing to an origin for the dust in a rocky body. Detailed inspection of elemental abundances in metal-rich WDs provides a unique insight into the composition of extrasolar planetesimals. Analyses of two metal-polluted WDs (GD 61, NLTT 43806) suggest that the accreted dust was derived from an asteroid whose origin was in the outer layers of a differentiated planet, in which the heaviest elements had sunk to the core, leaving a Ca-rich and possibly water-rich lithosphere (Farihi et al. 2011; Zuckerman et al. 2011).

3. Remnant planetary systems around white dwarfs

As the Galaxy grows old, WDs will become the most common stars, with ~98% of the current stellar population eventually evolving into WDs. It is likely that ~30% of all *current* Galactic WDs are orbited by remnant planetary systems that survived post-main sequence evolution of the progenitor stars (Zuckerman et al. 2010). Since planetary systems can survive the post-main sequence evolution of their parent star and, additionally, if some "second generation" planets are formed during this evolution, then most planets will eventually orbit WDs. The very existence of dusty WDs confirms that one or both of these processes is occurring – in the context of the asteroid disruption model, a WD circumstellar dust disk is indirect evidence of at least one massive planetary body acting as an orbital perturber.

3.1. Life, the Universe, and everything

This glimpse into the future of the Solar System (also see Di Stefano 2011) raises intriguing questions of interest to astronomers, biologists, and the general public: what will be the fate of the Earth and other terrestrial planets when the Sun evolves off the main sequence? What will happen to life in the Universe after galaxies become so old that star formation has ceased? It is not currently known exactly what range of conditions can support life, but many of the processes capable of producing enough energy to support life even in the absence of Sun-level luminosity, such as tidal interactions, will continue into the far future around WDs. Some of the WDs now known have been WDs for longer than it has taken for life to emerge on the Earth and evolve to its present state. In the far future, the most common environment in the Universe for supporting life may very well be planets orbiting WDs.

Due to the many extrasolar planet discoveries in recent years, the possibility of identifying a habitable planet outside our Solar System has become a tangible goal that captures the imaginations of scientists and non-scientists alike. Concurrent growth in our understanding of the conditions necessary to support life can now inform our relationship with our own planet. There are three planets (Venus, Earth, Mars) in the habitable zone of our Sun, yet only one supports life. Comparisons to these nominally habitable – yet uninhabited – planets offers a chilling appraisal of the potential long-term effects of global climate change on the Earth. In the distant future, some of our neighboring planets will survive the eventual transformation of the Sun into a WD, but can life persist as this feeble stellar remnant gradually cools until luminous energy can no longer provide life's driving impetus? Lessons learned from deep ocean life forms on Earth, which utilize thermal and chemical energy sources, can be drawn upon to speculate about the nature of life in a far-future Universe of faded WDs.

4. Dust in cataclysmic variables

Cataclysmic variables (CVs) were observed starting in the first Guest Observer cycle of *Spitzer*, and in every subsequent cycle. These observations probed longer wavelengths, at higher sensitivity, than in any previous IR observations of CVs. A remarkable early discovery from these *Spitzer* observations was the nearly ubiquitous presence of an IR excess signature attributable to thermal emission from dust (Howell et al. 2006; Brinkworth et al. 2007; Hoard et al. 2007; Howell et al. 2008; Hoard et al. 2009). As such, CVs join both single WDs (see above) and X-ray binaries (Muno & Mauerhan 2006) in possessing dust.

4.1. Dusty extension to the gaseous accretion disk

In some cases, the dust in CVs is found to be located within the Roche lobe of the WD. It survives the harsh environment near the hot WD by lurking in the shadow of the accretion disk, near the periphery of the Roche lobe Howell et al. (2008). This was found to be the case for both of the dwarf novae WZ Sge and Z Cha. The observational signatures of the presence and distribution of this dust are an IR excess (see Figure 3) accompanied by a mid-IR light curve displaying an eclipse that is significantly longer in duration than the optical eclipse (see Figure 4). The larger eclipse width (indicating a dusty extension to the accretion disk) can be seen in Figure 4. Other notable features of the *Spitzer* light curve of Z Cha are the lack of a pre-eclipse hump (which likely indicates that the temperature of the bright spot at the accretion stream impact site is high enough to shift the peak of its emission out of the IR), and the presence of a secondary eclipse, which is not seen in the optical light curve.

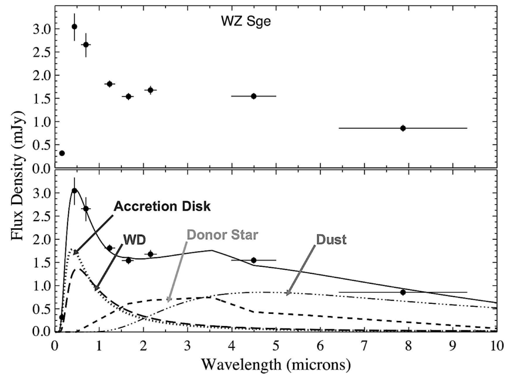

Fig. 3. Observed optical–IR spectral energy distribution (top) and model (bottom) for WZ Sge. The system model (solid line) is composed of a WD (dotted line), L5.0 secondary star (short-dashed line), steady state accretion disk (long-dashed line), and circumstellar dust ring (triple-dot-dashed line). See Howell et al. (2008) for more details.

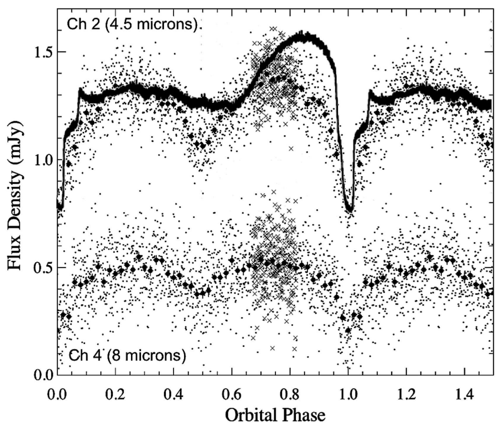

Fig. 4. *Spitzer* Infrared Array Camera light curves of Z Cha at 4.5 (top) and 8 μm (bottom), shown as individual 2-s exposures (small points) folded on the orbital ephemeris of Baptista et al. (2002), with $\Delta\phi = 0.01$ binned averages (large points). The optical light curve from Wood et al. (1986) (solid line) is superimposed on the 4.5 μm data.

Recently, Gaudenzi et al. (2011) reanalyzed all available *International Ultraviolet Explorer* UV spectra of the archetype dwarf nova SS Cyg, and determined the amount of reddening from the 2175 Å feature (which, incidentally, identifies the likely source of the reddening as complex carbon molecules; i.e., fullerenes, buckyoinions, etc). They observed a variable reddening component in excess of the constant interstellar reddening; indicating the likely presence of carbon-rich dust within the SS Cyg system[1]. The variable reddening was weakest shortly after outburst, and grew stronger thereafter, peaking at ~70–80% of the interval between outbursts. It also varied with orbital phase, with the strongest values around $\phi \sim 0.5$ (with a range of $\Delta\phi \sim 0.7$).

4.2. Circumbinary dust disks

In other cases, the dust is located in a circumbinary disk around the entire CV Hoard et al. (2009). The first confirmed example of this is the novalike CV V592 Cas, which was observed with all of the instruments on *Spitzer* to obtain a spectral energy distribution out to 24 μm (see Figure 5; Hoard et al. 2009). Such disks were suggested as possible sources of additional angular momentum loss contributing to the secular evolution of CVs Spruit & Taam (2001); Taam et al. (2003); Willems et al. (2005, 2007); however, the *Spitzer* results imply total dust masses many orders of magnitude too small to be effective in that respect Hoard et al. (2009). Lingering questions remain: what is the nature (composition, size, shape, etc.) of the dust? What is the origin of the dust? How rapidly (if at all) is the dust replenished and/or destroyed?

4.3. Circumstellar vs. circumbinary

An important, and discriminating, distinction between the two cases for the distribution of dust in CVs emerges from the dust disk models used to fit the IR excess. For example, in WZ Sge (see Figure 3), the dust is assumed to extend from an inner radius ($\approx$ 11 R_{wd}) corresponding to the dust sublimation temperature ($\approx$ 1500 K), to an outer radius ($\approx$ 30 R_{wd}) that is constrained by the lowest temperature con-

[1] Inasmuch as this is an independent confirmation of the presence of dust in a CV, that did not rely on data from *Spitzer* nor my direct involvement in the analysis, it comes as a relief to me!

sistent with the shape of the IR excess in the spectral energy distribution ($\approx$ 700 K). This sharp cutoff in temperature corresponds to a radius close to the WD Roche lobe, consistent with the dust extending outward from the edge of the accretion disk. In contrast, although the dust disk model in V592 Cas is constrained to also start at a specific radius (corresponding to the tidal truncation radius outside the CV), the IR excess out to 24 μm does not constrain the outer (i.e., low) dust temperature. This situation is consistent with a dust distribution with no sharp outer boundary and, instead, merges into the ambient ISM surrounding the CV.

5. Discussion – The differences between WD and CV dust disks

Upon initial comparison, the dust disks around WDs and CVs (both circumstellar and circumbinary) bear some striking similarities. For example, they both involve about the same total mass of dust, equivalent to a medium–large Solar System asteroid ($\sim 10^{21}$–10^{23} g; Hoard et al. 2009, Section 5.6.4 in Farihi 2011) and, of course, they are both in orbit around a WD. However, a more detailed inspection of the observational data demonstrates that this similarity is superficial (and coincidental). There are also significant differences in the properties of WD and CV dust disks that can be used to infer detailed characteristics of the properties and origin of both types of disks.

As described above, the origin of dust around WDs is securely established as a tidally disrupted asteroid that was perturbed into the WD Roche lobe by a remnant planet. While this scenario cannot be ruled out for CVs, it seems unlikely; there have been some recent claims for the presence of circumbinary planets around several CVs, but this issue is currently contested in the literature and has not been settled one way or the other (e.g., HU Aqr: Schwarz et al. 2009; Horner et al. 2011; Qian et al. 2011; Wittenmyer et al. 2012; DP Leo: Qian et al. 2010a; Beuermann et al. 2011; UZ For: Potter et al. 2011; QS Vir: Parsons et al. 2010; Qian et al. 2010b). More to the point, the creation of *circumbinary* dust around a CV cannot rely on tidal disruption of an asteroid.

A more likely scenario for the origin of dust in CVs is the coagulation of gaseous material (possibly already enriched with dust grains formed in the outer atmosphere of the secondary star) that is transported into the WD Roche lobe through the L1 point (in the case of WD circumstellar dust), or transported into circumbinary space via dwarf nova or nova outbursts, a wind or outflow from the accretion disk or secondary star, and/or as a natural consequence of the mass transfer process. Numerical simulations of the mass transfer process in a CV have demonstrated that as much as 50% of the matter transferred through the L1 point can escape from the WD Roche lobe and end up in circumbinary space around the CV (Bisikalo et al. 1998, 2003; Bisikalo & Kononov 2010; Bisikalo 2010).

A significant difference is the lack of a 10 μm silicate emission feature in CV dust disks (Hoard et al. 2007, 2009), which is prominently observed in WD dust disks (e.g., Jura et al. 2007, 2009; also see Figure 1). Figure 6 shows the mid-IR spectra of several CVs obtained with the IRS on *Spitzer*. None of these systems shows evidence for 10 μm emission. An explanation for this likely hinges on the dust grain size in each type of disk. As a rule of thumb, a spectral feature from dust at a particular wavelength is only present if the light-scattering grains are smaller than that wavelength (Koike et al. 1980; D'Alessio et al. 2006; Voshchinnikov & Henning 2008). Hence, we infer that dust grains in WD disks must have a characteristic size smaller than 10 μm, while the dust in CVs must be, on average, larger than 10 μm. A similar situation was found for the dust disk in the unique long-period eclipsing binary ϵ Aur which, like CVs, does not show a mid-IR silicate emission feature in its spectrum (Hoard et al. 2010). To provide a phenomenological comparison of the nature and origin of dust disks in WDs and CVs, I have developed the following schema.

WDs have "destructive" (or "hot") disks comprised of preferentially small grains ($\lesssim$ a few μm) created via recent and ongoing tidal disruption of asteroids or comets, followed by particulate collisions and grinding (similar to debris disks in young A type stars; e.g., Knacke

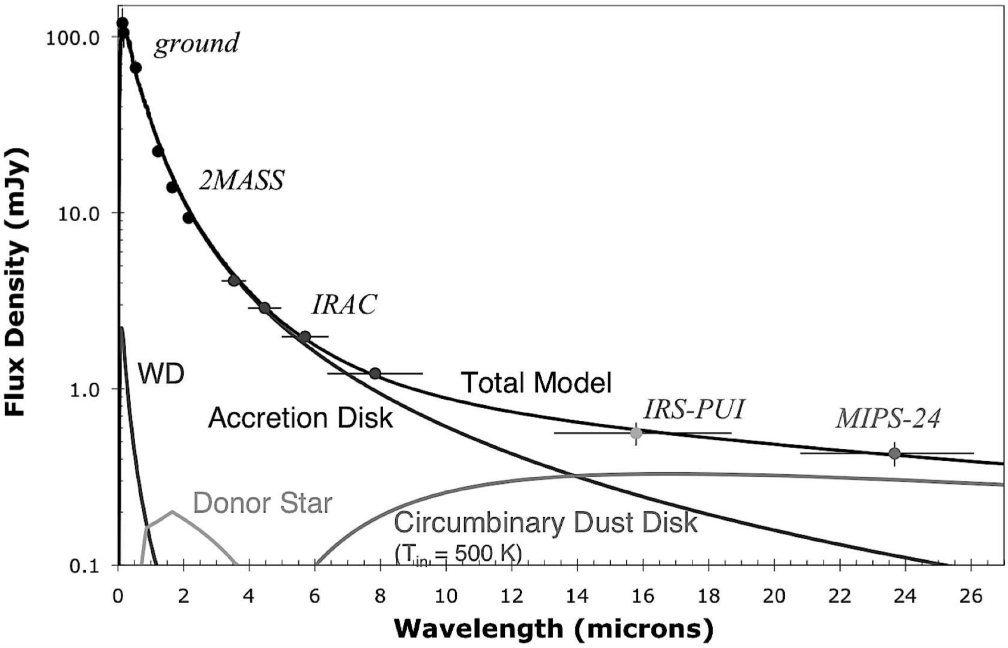

Fig. 5. Optical–mid-IR spectral energy distribution of V592 Cas (points) with a model consisting of a WD, low mass secondary star, accretion disk, and circumbinary dust disk (lines).

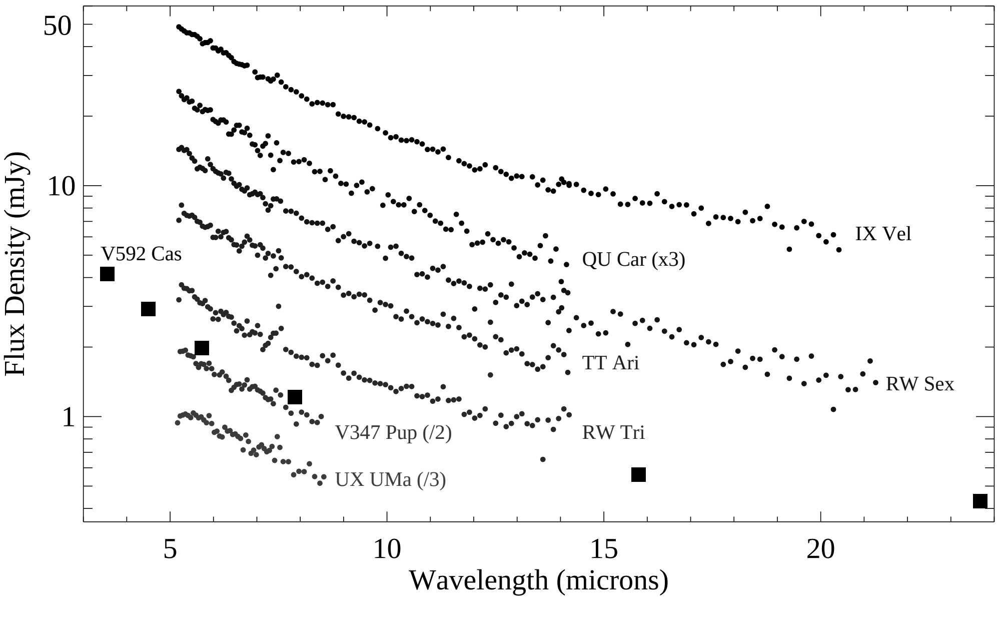

Fig. 6. Mid-IR spectra of seven CVs from the IRS on *Spitzer* (small points), along with the photometric data for V592 Cas from Figure 5 (large squares). (From Hoard et al. 2012.)

et al. 1993; Sylvester et al. 1996). These small grains survive because they are protected from the WD's radiation in the "shadows" of optically thick regions of the dust disk.

CVs have "constructive" (or "cold") disks comprised of preferentially large grains ($\gtrsim$ 10 μm) built via coagulation of smaller particles (gas & dust; Lommen et al. 2010) that ultimately originated from the secondary star. The accretion disk (if present) provides a "shadow" that protects dust in the orbital plane from the WD's radiation, but the grain size distribution could also be skewed to larger sizes because small particles are preferentially removed via radiation pressure and sublimation owing to the generally hotter WDs in CVs (plus the presence of the cool secondary star, which, because of its larger surface area, can make a more significant contribution to heating circumbinary dust than the WD).

6. Conclusions

In his 1927 book *Stars and Atoms*, the eminent early 20th century astronomer Arthur Stanley Eddington recalled the initial discovery of WDs, and the reaction of himself and his colleagues to the dawning realization that these objects were unlike any previously known star:

> "We learn about the stars by receiving and interpreting the messages which their light brings to us. The message of the Companion of Sirius when it was decoded ran: 'I am composed of material 3000 times denser than anything you have ever come across; a ton of my material would be a little nugget that you could put in a matchbox.' What reply can one make to such a message? The reply which most of us made in 1914 was – 'Shut up. Don't talk nonsense.' "

I imagine that a similar reaction might have been appropriate if, a couple decades ago, the assertion had been made that dust grains, fragile and frangible, would be found to be commonly present in the harsh environments, bathed in UV light and high temperature, surrounding WDs, both singly and in CVs. Yet, this has been increasingly demonstrated observationally. While the total amount of dust in both situations is relatively insignificant, the implications of its presence are far-reaching. In the case of single WDs, the dust points a finger at the post-main sequence survival of planetary systems and offers an opportunity to explore the chemical composition of extrasolar planetary material. In the case of CVs, the dust offers constraints on our understanding of the processes of mass transfer and accretion. In both cases, the recent discovery of dust in WDs and CVs provides a valuable reminder that even objects which have been extensively studied, and were thought to be relatively uncomplicated and well understood, can surprise us with the unexpected.

Acknowledgements. I want to acknowledge and thank my many collaborators on the various projects summarized herein, especially (but not exclusively!) John Debes, Steve Howell, Knox Long, Paula Szkody, and Stefanie Wachter. This work is based in part on observations made with the *Spitzer Space Telescope*, which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with NASA. Support for this work was provided by NASA through an award issued by JPL/Caltech. This work utilizes data products from the Two Micron All Sky Survey, a joint project of the University of Massachusetts and the Infrared Processing and Analysis Center/Caltech, funded by NASA and the NSF, and was facilitated by the SIMBAD database, operated at CDS, Strasbourg, France, and NASA's Astrophysics Data System.

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