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Comets Prancing around Dying Stars?

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Abstract

White dwrafs (WDs) are the final evolutionary product of stars similar to our Sun. Astronomers have been searching for planets and dust disks around WDs using excess infrared (IR) emission as diagnostics. Most searches have been using near-IR observations for WDs of temperatures a few 10^4 K. Recent *Spitzer Space Telescope* observations of the Helix Nebula revealed a bright mid-IR source at its central star, a 110,000 K hot WD. This mid-IR source has been analyzed and shown to originate from a dust disk at 50-100 AU from the star. This dust disk is most likely produced by collisions among Kuiper-Belt-like objects, or comets. To determine whether the Helix central star is unique, we have surveyed a large number of hot WDs and found several objects that show similar mid-IR excesses. Interestingly, they are all associated with planetary nebulae. Do they all have comets prancing around the central dying stars? At least one WD may have a companion accreting the mass loss from its progenitor. Follow-up observations will be made to solve this puzzle.

1. Introduction

Astronomers have been finding planetary systems around stars that are similar to our Sun (Butler et al. 2006). While the physical properties of these extrasolar planets have been actively pursued, some attention has been turned to the search for planetary systems around evolved stars. The discovery of a massive planet around an intermediate-mass red giant suggests that at least some planets can survive through the initial stellar evolution (Lovis and Mayor 2007). Do planetary systems survive through the end of stellar evolution?

Before tackling this problem, I will briefly describe the process of stellar evolution. Stars with masses up to ~8 Msun evolve off the main sequence and shed the stellar envelope via copious slow winds at the red giant branch (RGB) or asymptotic giant branch (AGB). As the stellar core is gradually exposed, the observed effective temperature rises and the slow wind is replaced by a tenuous fast wind. The fast wind catches up and sweeps up the previous slow wind to form a shell, and when the shell is photoionized by the stellar UV radiation, a planetary nebula (PN) is born. The fast wind diminishes as the stellar envelope is stripped. Eventually, the PN expands and fades away and the central star becomes a cooling white dwarf (WD).

Although the most massive WDs have masses near 1.4 Msun, the Chandrasekhar's limit, the majority of WDs have masses ~0.6 Msun. These WD masses are just a small fraction of the initial stellar masses, which are up to ~ 8 Msun. Having lost more than ½ of its initial mass, the star and its planetary system are no longer gravitationally bound. The planets would migrate further and further away from the WD and become more and more difficult to detect. It is thus not surprising that no planets have been discovered around WDs.

Planetary systems may contain small bodies orbiting in congregations, analogous to the asteroids and Kuiper-Belt objects (KBOs) in the solar system. As the central star loses more than ½ of its mass, the outward expansion would lead to more collisions among small bodies in the Asteroid Belt and Kuiper Belt. The collisions result in several consequences. First, colliding asteroids or KBOs can be pulverized and produce a dust disk. Second, after a narrowly missed collision, an asteroid can change its orbit and travel close to the central star, and if the impact parameter is within the Roche limit the asteroid will be tidally disrupted and form a dust cloud or a dust disk. If the asteroid makes a direct hit on the central star, the impact would produce shock heating and may emit in X-rays. The accretion of asteroid dust or impact of asteroid may enrich the atmosphere of a WD. There have been numerous successes in detecting dust disks around WDs produced by crushed asteroids.

Dust disks around WDs cannot be confused with debris disks, the relics from the original star formation, because the debris disks commonly seen around main sequence stars decay over a timescale of ~0.5 Gyr (Rieke et al. 2005). The decay results from dust being driven out by radiation pressure or stellar wind, or spiraling into the star due to Poynting-Robertson effect.

Dust disks around WDs have been diagnosed by the excess infrared (IR) emission over the stellar photospheric emission, such as G 29-38 and GD 362 (Becklin et al. 2005; Reach et al. 2005). Figure 1 shows the spectral energy distribution (SED) of the WD G 29-38, in which the IR excess and a silicate spectral feature at 10 μm are clearly visible. Surveys for WDs with IR excesses

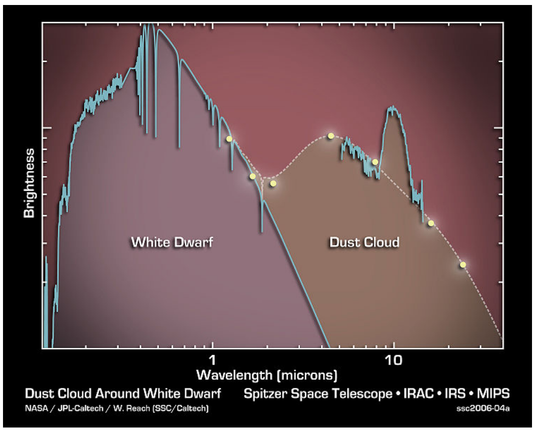

Fig. 1: Spectral energy distribution of the white dwarf G 29-38 (Reach et al. 2005).

have obtained limited successes; for example, a Spitzer Space Telescope survey of 124 WDs at 4.5 and 8.0 μm found only one new case of dust disk (Mullally et al. 2007). As the accretion of asteroidal material can enrich the atmosphere of a WD, changing its spectral type from DA (hydrogen-rich) to DAZ (hydrogen-rich but also showing heavy elements). Surveys for dust disks have been conducted for DAZ WDs, and indeed higher success rates are obtained (Kilic and Redfield 2007; Jura et al. 2007). It is now well established that dust disks around DAZ WDs within < 0.01 AU radii are produced by tidally disrupted asteroids and that they are best diagnosed by near-IR excess. The WDs also have to be cooler than ~25,000 K so that the dust temperature is below the sublimation temperature of ~1,500 K.

How about the dust disks produced by colliding comets in the Kuiper Belt?

2. The Helix Nebula's Central WD

The WD at the center of the Helix Nebula, WD 2226-210, was detected by ROSAT to show both soft X-ray emission below 0.4 keV and hard X-ray emission near 1 keV (Leahy et al. 1996). The soft X-ray emission originates from the hot stellar phorosphere, but the 1 keV emission cannot be explained. A deep Chandra ACIS observation of the Helix shows that both the soft and hard components of the X-ray emission are unresolved and coincident with WD 2226-210 (Guerrero et al. 2001). While the high-resolution Chandra observation confirms that the 1 keV X-ray emission originates from the immediate vicinity of the star, WD 2226-210 is not known to have a binary companion. A sensitive search using HST images has ruled out any companion with a spectral type earlier than M5 (Ciardullo et al. 1999).

Following Occam's razor, Guerrero et al. (2001) and Gruendl et al. (2001) suggested that the Helix central star had a late-type M companion whose coronal emission contributed to the 1 keV emission, because its 1 keV X-ray luminosity and Hα emission line profile showed temporal variations. To verify the existence of a late-type companion for the Helix central star, we examined the Spitzer observations in the IR. To our surprise, the IRAC 3.6, 4.5, and 5.8 μm observations rule out the existence of even a late T-type companion, while the MIPS 24 μm observations show a compact source coincident with the star (Figure 2). A follow-up Spitzer IRS spectrum has verified that the mid-IR emission originates from dust continuum (Figure 3). The spectral energy distribution of this IR-emitter (Figure 4) indicates a temperature of 90-130 K, too cold to be a star or brown dwarf. The IR luminosity, $5\text{-}11\times10^{31}$ ergs s^{-1}, requires a surface area of 4-40 AU^2, too large for planets. Only a dust disk can explain these properties (Su et al. 2007).

What is the nature of the dust disk around the central WD of the Helix Nebula? Given that WD 2226-210 has an effective temperature of 110,000 K (Napiwotzki 1999), the 90-130 K dust disk is expected be at a distance of 40 - 100 AU. This distance corresponds to that of the Kuiper Belt in the solar system. It is most likely that the dust disk is produced by collisions of KBOs or break-up of comets (Su et al. 2007). The presence of the KBOs may even explain the 1 keV X-ray emission, if some KBOs have gone astray and hit the central WD, the gravitational energy released and the shock heating of the WD's atmosphere may produce hot gas and emit in X-rays.

It is natural to ask whether more WDs are surrounded by dust disks similar to that of the Helix Nebula's central star.

Fig. 2: Spitzer color composite of the Helix Nebula with 3.6-4.5 μm in blue, 5.8-8.0 μm in green, and 24 μm in red. The central star is bright at 24 μm (Su et al. 2007).

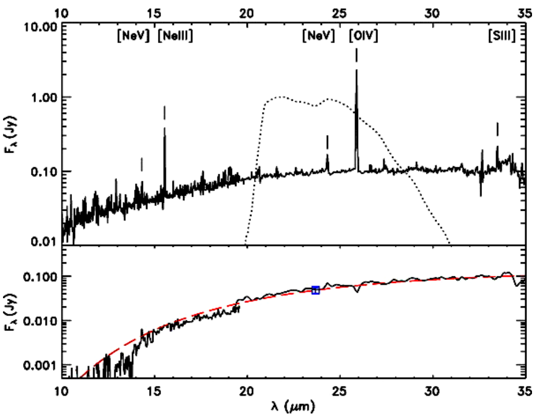

Fig. 3: Spitzer IRS spectrum of the central star of the Helix Nebula (Su et al. 2007). The upper and lower panels show the spectrum extracted at the central star before and after the background-subtraction. The nebular lines and response curve of the MIPS 24 μm band are marked in the upper panel. The blue square marks the MIPS 24 μm photometric measurement, and the red dashed curve is a dusty ring model.

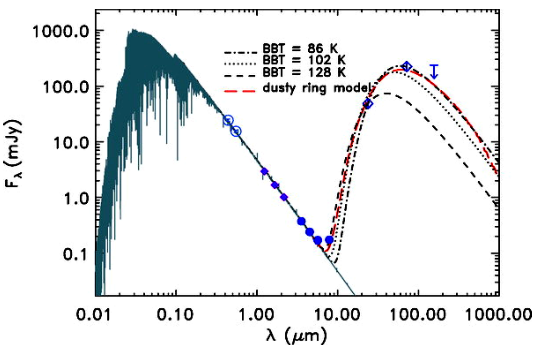

Fig. 4: Spectral energy distribution of the Helix Nebula's central star (Su et al. 2007). The IR excess peaks at 24-70 μm. Several models of dust emission are over-plotted.

3. Spitzer 24 μm Survey of Hot WDs

Dust disks produced by collisions among KBOs are detectable only for a limited period of time because of evolutionary effects. Only the hottest WDs' dust disks can be heated to temperatures high enough for their SEDs to peak in the mid- to far-IR wavelength range. As the WDs cool, the dust temperatures drop, shifting the emission peak out of the IR wavelength range. Furthermore, as the KBOs and comets expand away from the central star, the collision rate drops, and the dust disk will dissipate below detection limit. Therefore, to determine whether the dust disk around the Helix central star is a common event, a survey of hot, young white dwarfs in the mid-IR wavelengths is needed.

Therefore, we have used Spitzer MIPS to carry out a 24 μm survey of hot WDs, with stellar effective temperatures ~100,000 K or higher, to search for dust disks associated with KBOs and comets at distances of 50-100 AU from the central star, similar to the dust disk around the Helix central star. A sample of 72 hot WDs or pre-WDs is selected for the survey. About 50% of these young WDs are still surrounded by PNe, but all of these PNe are angularly large and well-resolved from the central stars.

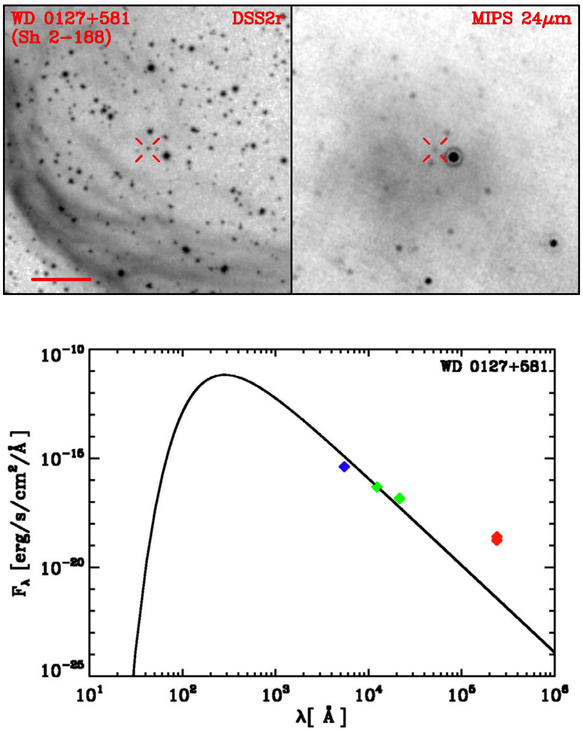

Fig. 5. Digitized Sky Survey red (DSSr) image and Spitzer MIPS 24 μm image of WD 0127+581 in the PN Sh 2-188. The WD is marked. Both images have the same scale; the scale bar in the left panel indicates 1 arcmin. The bottom panel shows the spectral energy distribution. A blackbody curve passing through the optical and near-IR data points is plotted to approximate the stellar photospheric emission.

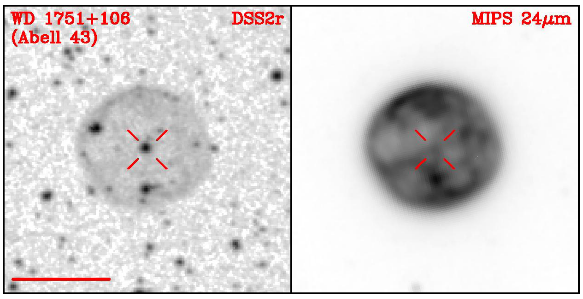

Fig. 6: Digitized Sky Survey red (DSSr) image and Spitzer MIPS 24 μm image of WD 1751+106 in the PN Abell 43. There is a hint of point source at the central WD, but it is overwhelmed by the bright nebular [O IV] 25.9 μm emission.

Among the 72 WDs observed, an unresolved 24 μm source coincident with the WD is clearly detected in 8 cases, and hints of 24 μm point sources superposed on bright nebular emission are seen in another 5 cases. Figure 5 shows images of WD 0127+581 in the PN Sh 2-188; the WD is clearly detected in the 24 μm image and its SED shows clear excess IR emission at 24 μm. WD 0127+581 is superposed on diffuse nebular emission that is most likely dominated by [O IV] 25.9 μm and [Ne V] 24.3 μm lines, as in the case of the Helix Nebula. In the example shown in Figure 6, the nebular line emission from the PN Abell 43 by far dominates the possible continuum emission from the central star WD 1751+106, making photometric measurements highly uncertain..

Do all these 24 μm sources at hot WDs originate from dust disks around the WDs?

4. Origin of the 24 μm Emission

While the 24 μm emission from the WD in the Helix Nebula is confirmed to be dust continuum, it is not clear whether the 24 μm emission from the other hot WDs has a similar nature. In the case of WD 0726+133 (in the PN Abell 21), archival HST images show that the WD appears to be single. However, in the case of WD 0950+136 (in the PN EGB 6), the IR excess and the forbidden nebular line emission have been shown to belong to a companion 0.18″ from the WD (Fulbright and Liebert 1993; Bond 1994). It is also possible that the 24 μm emission originates from dusty stellar ejecta similar to the H-deficient ejecta in the born-again PN Abell 30 and Abell 78 (Cohen and Barlow 1974; Borkowski et al. 1994, 1995).

Follow-up observations are needed to determine the nature of the 24 μm emission from hot WDs: (1) Spitzer IRS spectra of these 24 μm sources to determine whether nebular lines or dust continuum dominates the emission, observations of four hot WDs with 24 μm excesses are underway; (2) HST WFPC3 or ACS images in both Hα and [O III] lines and line-free continuum to determine whether H-deficient stellar ejecta and companion stars are present; (3) high-dispersion echelle spectra of the hot WDs to kinematically separate the nebular emission and stellar emission in order to determine the constituents within the MIPS point spread function at 24 μm; and (4) ground-based images in the HeII λ4686 line to search for HeII emission, which should co-exist with the [O IV] 25.9 μm emission.

Clearly, there is still a lot of work to do to determine whether the 24 μm emission detected from hot WDs is indeed dust continuum emission and whether the dust has been generated by collisions among KBOs, or *comets prancing around a dying star*.

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