Hard X-ray and Infrared Emission from Apparently Single White Dwarfs

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Abstract. The photospheric emission of a white dwarf (WD) is not expected to be detectable in hard X-rays or the mid-IR. Hard X-ray (~1 keV) emission associated with a WD is usually attributed to a binary companion; however, emission at 1 keV has been detected from three WDs without companions: KPD 0005+5106, PG 1159, and WD 2226−210. The origin of their hard X-ray emission is unknown, although it has been suggested that WD 2226−210 has a late-type companion whose coronal activity is responsible for the hard X-rays. Recent Spitzer observations of WD 2226−210 revealed mid-IR excess emission indicative of the existence of a dust disk. It now becomes much less clear whether WD 2226−210's hard X-ray emission originates from the corona of a late-type companion or from the accretion of the disk material. High-quality X-ray observations and mid-IR observations of KPD 0005+5106 and PG 1159 are needed to help us understand the origin of their hard X-ray emission.

1. Hard X-ray Emission from Apparently Single White Dwarfs

White dwarfs (WDs) can be associated with three types of X-ray sources: (1) photospheric X-ray emission from the WD itself, (2) accretion of material from a close binary companion, as in cataclysmic variables, and (3) coronal X-ray emission from a late-type binary companion, such as dMe stars. The latter two types of sources originate from WDs in binary systems and commonly show X-ray emission at 1 keV. In contrast, the photospheric X-ray emission from WDs is much softer, well below 0.5 keV. No hard X-ray emission is expected from single WDs.

Inspired by the hard X-ray emission from WD 2226−210, the central star of the Helix Nebula (Guerrero et al. 2001), we made a systematic search for hard X-ray emission from WDs using the WD catalog compiled by McCook & Sion (1999) and the Second ROSAT Source Catalogs of Pointed Observations with the PSPC with and without the Boron Filter (2RXF and 2RXP). Among the 124 X-ray sources that are found coincident with WDs, 22 show hard X-ray emission peaking near 0.8-0.9 keV. After identifying binary systems and extraneous X-ray sources, we find two WDs, KPD 0005+5106 (= WD 0005+511) and PG 1159 (= WD 1159−034), that are associated with hard X-ray emission and appear to be single (O’Dwyer et al. 2003; Chu et al. 2004a).
Figure 1. ROSAT PSPC observations of KPD0005+5106, PG 1159, and WD 2226−210. The top two rows show soft (0.1–0.4 keV) and hard (0.6–2.4 keV) band images. The poor point-spread-function in the soft band is caused by an electronic ghost image at energies below 0.2 keV. The bottom row shows the PSPC spectra. To show the hard counts of PG 1159, its spectrum above 0.6 keV is scaled up by a factor of 50 as marked and plotted in open symbols.

The hard X-ray emission from these three apparently single WDs is illustrated in Figure 1. The ROSAT Position Sensitive Proportional Counter (PSPC) images in the 0.6–2.4 keV energy band show clearly point sources coincident with the WDs, and the PSPC spectra show distinct emission near 1 keV.

1.1. KPD 0005+5106

KPD 0005+5106 was detected in the ROSAT All Sky Survey, and the analysis of its soft X-ray emission led to the suggestion of a (2–3)×10^5 K corona (Fleming et al. 1993). The 1 keV hard X-ray emission was detected in a pointed ROSAT PSPC observation made with the boron filter (O'Dwyer et al. 2003). KPD 0005+5106 has been observed with the Chandra Low Energy Transmission Grating Spectrometer. This observation detected only the soft X-ray emission,
and the spectrum can be described well by non-LTE photospheric models that contain some Fe, but the models cannot reproduce the 1 keV emission detected by ROSAT (Drake & Werner 2005).

KPD 0005+5106 does not have any known companion. Its photometric measurements ($V=13.32$, $J=13.93$, $H=14.13$, $K=14.18$) do not show an IR excess (O'Dwyer et al. 2003). The lack of IR excess and the presence of hard X-ray emission together place even more stringent constraints against the existence of a late-type companion (Chu et al. 2004b). The ROSAT PSPC count rate, $0.005 \pm 0.001$ counts s$^{-1}$ in the 0.4–2.0 keV band with the boron filter is estimated to correspond to roughly an X-ray luminosity of $L_X = (0.4–4) \times 10^{30}$ ergs s$^{-1}$. If this hard X-ray emission originates from the corona of a late-type companion with a canonical $L_X/L_{bol} = 10^{-3}–10^{-4}$, this companion should have $K=11–12$, but this is much brighter than the observed $K=14.18$. Therefore, the hard X-rays of KPD 0005+5106 cannot originate from the corona of a late-type companion.

KPD 0005+5106 had numerous high-dispersion spectroscopic observations. Using IUE observations, Holberg et al. (1998) reported average velocities of the photospheric NV and CIV lines (36.2 km s$^{-1}$), circumstellar NV, SiIV, and CIV lines (−6.2 km s$^{-1}$), and interstellar N I, C II, Si II, and S II lines (−7.5 km s$^{-1}$). Recently, using FUSE observations, Otte, Dixon, & Sankrit (2004) discovered an OVI-emitting nebula around KPD 0005+5106. Chu et al. (2004b) have analyzed the nebular environment of KPD 0005+5106, using radial velocities of all lines and spatial distributions of the emission lines. They show that KPD 0005+5106 resides in a photoionized interstellar H II region with a density of $\sim 0.8$ H-atom cm$^{-3}$. This interstellar H II region is responsible for the high-ionization “circumstellar” lines reported by Holberg et al. (1998). Therefore, there is no evidence of a circumstellar nebula or wind outflow from KPD 0005+5106.

While the ROSAT PSPC resolution cannot exclude the possibility of a chance superposition of a background AGN X-ray source near KPD 0005+5106, the stellar O VIII emission (Werner et al. 1996; Sion et al. 1997) places a strong constraint on the location of the hard X-ray source. The O VIII line is emitted from recombinations of O$^{+8}$. As the excitation potential of O$^{+8}$ is 871 eV, energetic photons are needed; thus, the hard X-ray source must be local to KPD 0005+5106. The origin of the hard X-ray emission from KPD 0005+5106 is most puzzling.

1.2. PG 1159

PG 1159 is a bright soft X-ray source. Its hard X-ray emission was detected in two independent ROSAT PSPC observations, RP701202N00 (13.6 ks) without the boron filter and RF200430N00 (9.8 ks) with the boron filter. Each observation detected 12±3 counts in the 0.6–2.4 keV band.

PG 1159 does not have any known companion. Its photometric measurements ($V=14.89$, $J=15.58$, $H=15.87$, $K=15.78$) do not show an IR excess (O’Dwyer et al. 2003). PG 1159 is a pulsator; therefore, a stellar companion can be definitively ruled out by high-precision measurements of its pulsation modes (Kawaler & Bradley 1994).

Both the presence of hard X-ray emission and the single-star status of PG 1159 are well established. The point spread function of the ROSAT PSPC...
has a FWHM of 30″–40″. Both the spectral shape and the spatial coincidence between the hard X-ray source and PG 1159 can be improved by a deep Chandra or XMM-Newton observation.

1.3. WD 2226−210

WD 2226−210 is the central star of the Helix Nebula. Chandra ACIS-S observations show a point X-ray source coincident with the star within 0′′.5. The ACIS spectrum can be fitted by a thin plasma emission model with a temperature of (7–8)×10⁶ K and an X-ray luminosity of \( L_X = 3 \times 10^{29} \) ergs s⁻¹ in the 0.3–2.0 keV range. These X-ray properties and the 25% decline of the X-ray luminosity during the period of Chandra observation prompted Guerrero et al. (2001) to suggest the existence of a dMe companion. This hypothesis is supported by the observed variability of the stellar Hα emission line profile (Gruendl et al. 2001).

An HST search for companions of WD 2226−210 has yielded null results, indicating that no companion earlier than M5 exists (Ciardullo et al. 1999). If there is a late type companion, its luminosity has to be lower than 4.2×10³¹ ergs s⁻¹. If this hypothetical companion is responsible for the hard X-ray emission, its \( L_X/L_{bol} \) is ≥7×10⁻³, much higher than the canonical 10⁻⁴–10⁻³. It is uncertain whether WD 2226−210 indeed has a late-type dMe companion. It is also puzzling how a late-type dMe star can have such a high \( L_X/L_{bol} \).

2. Mid-Infrared Excess of WD 2226−210

Excess emission at near-IR wavelengths is often used to diagnose the presence of a late-type companion. The Helix central star has no near-IR excess; however, a mid-IR excess is revealed by observations made with the Spitzer Space Telescope IRAC at 3.6, 4.5, 5.8, and 8.0 μm and MIPS at 24, 70, and 160 μm (Su et al. 2006). The central star, WD 2226−210, is detected at all except the 160 μm MIPS band. Figure 2 presents the Spitzer images of the Helix at 3.6, 8.0, 24, and 70 μm. The 24 μm band shows a prominent point-like source at the central WD, superposed on an extended region of diffuse emission. A Spitzer IRS spectrum of the diffuse emission region shows that the [O IV] 25.89 μm line is the major contributor to the flux in the 24 μm band (see Figure 3a). No IRS spectrum of the central point-like source is available.

To determine whether the central point-like source is also dominated by the [O IV] 25.89 μm line emission in the 24 μm band, we compare the 24 μm image with a He II λ4686 image. The excitation potential of O IV, 54.9 eV, is similar to the ionization potential of He II, 54.4 eV; therefore, regions emitting [O IV] 25.89 μm line should emit He II λ4686 line, too. The He II image of the Helix Nebula (O'Dell 1998) shows a central diffuse emission region similar to that seen at 24 μm, but not a point-like central source. Thus, we conclude that the [O IV] line does not contribute to the central point-like source in the 24 μm band. It is possible that the central source is dominated by the [Ne V] 24.32 μm line in the 24 μm band, then the emission in the 70 μm band would have to be dominated by high-ionization lines, but the 70 μm band contains only low-ionization lines. Thus, it is most likely that the central point-like source detected in the MIPS 24 and 70 μm bands is a continuum source.
Figure 2. *Spitzer Space Telescope* images of the Helix Nebula.

Figure 3. (a) *Spitzer* IRS spectrum of the central diffuse emission region of the Helix Nebula. The dotted curve shows the MIPS band. (b) The spectral energy distribution of the central point-like source that is coincident with WD 2226−210. Three blackbody models and a dusty ring model are overplotted.
The spectral energy distribution (SED) of WD 2226–210 is presented in Figure 3b. The optical and near-IR emission follows the Rayleigh-Jeans tail, but the mid-IR emission rises sharply at 24 µm and remains high at 70 µm. This mid-infrared excess is consistent with a 100–130 K blackbody emitter. No stars have such a low temperature. If this IR excess emission is re-processed stellar emission, the emitting material must be several tens of AU from WD 2226–210, which has a stellar effective temperature of ∼110,000 K. For a distance of 210 pc (Harris et al. 1997), the 24 µm band luminosity, ∼9 × 10^{30} ergs s^{-1}, requires an emitting area of almost 10 AU^2. The temperature and distribution of the emitting material suggest that it is a dust disk.

Dust disks have been observed around WDs, such as GD 362 and G 29-38 (Becklin et al. 2005; Kilic et al. 2005; Zuckerman & Becklin 1987; Reach et al. 2005), but these dust disks are at smaller distances from their central WDs and have higher temperatures.

3. Hard and Mid-Infrared Emission from Apparently Single WDs

Hard X-ray emission from the three apparently single WDs, KPD 0005+5106, PG 1159, and WD 2226–210, is puzzling. The discovery of a dust disk around WD 2226–210 opens up the possibility that the accretion of disk material gives rise to the hard X-ray emission. The detailed process is still unknown. High-quality X-ray observations of KPD 0005+5106 and PG 1159 can provide spectral and temporal properties of their hard X-rays and shed light on the origin of the X-ray emission. Mid-IR observations of these two WDs are also needed to see whether they also have a dust disk.

References

Becklin, E. E., et al. 2005, ApJ, 632, L119
Chu, Y.-H., et al. 2004b, AJ, 128, 2357
Chu, Y.-H., Guerrero, M. A., Gruendl, R. A., & Webbink, R. F. 2004a, AJ, 127, 477
Ciardullo, R., et al. 1999, AJ, 118, 488
Drake, J. J., & Werner, K. 2005, ApJ, 625, 973
Fleming, T. A., Werner, K., & Barstow, M. A. 1993, ApJ, 416, L79
Gruendl, R. A., Chu, Y.-H., O’Dwyer, I. J., & Guerrero, M. A. 2001, AJ, 122, 308
Guerrero, M. A., Chu, Y.-H., Gruendl, R. A., Williams, R. M., & Kaler, J. B. 2001, ApJ, 553, L55
Harris, H. C., Dahn, C. C., Monet, D. G., & Pier, J. R. 1997, IAU Symp. 180, 40
Holberg, J. B., Barstow, M. A., & Sion, E. M. 1998, ApJS, 119, 207
Kawaler, S. D., & Bradley, P. A. 1994, ApJ, 427, 415
Kilic, M., von Hippel, T., Leggett, S. K., & Winget, D. E. 2005, ApJ, 632, L115
McCook, G. P. & Sion, E. M. 1999, ApJS, 121, 1
O’Dell, C. R. 1998, AJ, 116, 1346
O’Dwyer, I. J., Chu, Y.-H., Gruendl, R. A., Guerrero, M. A., & Webbink, R. F. 2003, AJ, 125, 2239
Otte, B., Dixon, W. V. D., & Sankrit, R. 2004, ApJ, 606, L143
Reach, W. T., et al. 20055, ApJ, 635, L161
Sion, E. M., Holberg, J. B., Barstow, M. A., & Scheible, M. P. 1997, AJ, 113, 364
Su, K. Y.-L., et al. 2006, ApJ, submitted
Werner, K., et al. 1996, A&A, 307, 860
Zuckerman, B., & Becklin, E. E. 1987, Nature, 330, 138