



A Candidate Giant Planet Companion to the Massive, Young White Dwarf GALEX J071816.4+373139 Informs the Occurrence of Giant Planets Orbiting B Stars

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Abstract

It has been suggested that giant planet occurrence peaks for stars with $M_* \approx 3 M_\odot$ at a value a factor of 4 higher than observed for solar-mass stars. This population of giant planets predicted to frequently orbit main-sequence B stars at $a \approx 10$ au is difficult to characterize during the few hundred million years while fusion persists in their host stars. By the time those stars become massive, young white dwarfs, any giant planets present would still be luminous as a consequence of their recent formation. From an initial sample of 2195 Gaia-identified massive, young white dwarfs, we use homogeneous Spitzer Infrared Array Camera (IRAC) photometry to search for evidence of unresolved giant planets. For 30 systems, these IRAC data provide sensitivity to objects with $M \lesssim 10 M_{\text{Jup}}$, and we identify one candidate with $M \approx 4 M_{\text{Jup}}$ orbiting the white dwarf GALEX J071816.4+373139. Correcting for the possibility that some of the white dwarfs in our sample result from mergers, we find a giant planet occurrence $\eta_{\text{GP}} = 0.11^{+0.13}_{-0.07}$ for stars with initial masses $M_* \gtrsim 3 M_\odot$. Our occurrence inference is consistent with both the Doppler-inferred occurrence of giant planets orbiting $M_* \approx 2 M_\odot$ giant stars and the theoretically predicted factor of 4 enhancement in the occurrence of giant planets orbiting $M_* \approx 3 M_\odot$ stars relative to solar-mass stars. Future James Webb Space Telescope NIRCarn observations of our sample would provide sensitivity to Saturn-mass planets and thereby a definitive estimate of the occurrence of giant planets orbiting stars with $M_* \gtrsim 3 M_\odot$.

Unified Astronomy Thesaurus concepts: B stars (128); Exoplanet detection methods (489); Exoplanet formation (492); Exoplanets (498)

1. Introduction

The relationship $\eta_{\text{GP}}(M_*, Z)$ between giant planet occurrence η_{GP} and the masses M_* and metallicities Z of their host stars has provided some of the strongest evidence in support of the core-accretion model of giant planet formation (e.g., J. B. Pollack et al. 1996; O. Hubickyj et al. 2005). For dwarf stars in the interval $0.3 M_\odot \lesssim M_* \lesssim 1.0 M_\odot$, $\eta_{\text{GP}}(M_*)$ is correlated with M_* (e.g., R. P. Butler et al. 2006; A. Cumming et al. 2008). These observations confirmed theoretical predictions put forward by G. Laughlin et al. (2004) and S. Ida & D. N. C. Lin (2005). Likewise, $\eta_{\text{GP}}(M_*)$ increases with M_* in the interval $1.0 M_\odot \lesssim M_* \lesssim 2.0 M_\odot$ with the caveat that $\eta_{\text{GP}}(M_*)$ inferences are based on dwarf stars at the low end of that interval and evolved stars with much larger stellar pulsations at the high end of that interval (e.g., J. A. Johnson et al. 2010; L. Ghezzi et al. 2018; V. Wothoff et al. 2022). $\eta_{\text{GP}}(M_*, Z)$ increases with Z over the mass interval $0.3 M_\odot \lesssim M_* \lesssim 2.0 M_\odot$, with some suggestion that the strength of the dependence of $\eta_{\text{GP}}(M_*, Z)$ on Z is diminished at the high-mass end of that interval (e.g., N. C. Santos et al. 2004; D. A. Fischer & J. Valenti 2005; S. Hekker & J. Meléndez 2007; L. Pasquini et al. 2007; Y. Takeda et al. 2008; J. Maldonado et al. 2013; S. Reffert et al. 2015; M. I. Jones et al. 2016; R. A. Wittenmyer et al. 2017; V. Wothoff et al. 2022).

Taken together, the observations that $\eta_{\text{GP}}(M_*, Z)$ increases with both M_* and Z confirms the key prediction of the core-accretion model of giant planet formation that cores of giant planets can assemble more quickly in disks with larger complements of solid material. Gaseous disks orbiting young stars are observed to dissipate more quickly for massive stars, though, so while the timescale for core formation decreases for massive stars, so does the time available for giant planet formation (e.g., J. M. Carpenter et al. 2006; G. M. Kennedy & S. J. Kenyon 2009; V. Roccataliata et al. 2011; C. Yasui et al. 2014; Á. Ribas et al. 2015). The net result of these two effects is that at constant metallicity the function $\eta_{\text{GP}}(M_*)$ should peak somewhere in the interval $M_* \gtrsim 1 M_\odot$, with the exact value sensitively dependent on the details of the planet formation process (e.g., S. Ida & D. N. C. Lin 2005; G. M. Kennedy & S. J. Kenyon 2008; K. A. Kretke et al. 2009). The measurement of $\eta_{\text{GP}}(M_*)$ for the most massive stars with $M_* \gtrsim 3 M_\odot$ would therefore provide critical empirical constraints on the giant planet formation process.

The observational characterization of the giant planet population orbiting stars with $M_* \gtrsim 3 M_\odot$ is extraordinarily difficult with the Doppler and transit techniques responsible for the discovery and characterization of most known exoplanets. Massive stars have large-amplitude pulsations, fast rotation, and few absorption lines, all of which make it very hard to discover and characterize planets with the Doppler technique. The pulsations and large radii of massive stars complicate searches for planets using the transit technique, too, and the Doppler confirmation of candidate transiting planets faces the same problems. Because the water-



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ice lines in the massive protoplanetary disks initially present around $M_* \gtrsim 3 M_\odot$ stars will lie beyond 10 au, the relatively wide-separation planets predicted to form would be invisible to the Doppler or transit techniques, even without the difficulties described above.

The expected peak of the giant planet population orbiting stars with $M_* \gtrsim 3 M_\odot$ is also inaccessible with direct imaging techniques. Since solar metallicity stars with $M_* \gtrsim 3 M_\odot$ leave the main sequence in less than about 400 Myr, main-sequence stars with $M_* \gtrsim 3 M_\odot$ must be young and therefore attractive targets for the direct imaging technique. Massive stars are uncommon, though, as only 18 such stars are present in the Gaia Early Data Release 3 (EDR3) 100 pc sample (Gaia Collaboration et al. 2021b). Those 18 massive stars have a median distance in excess of 90 pc and $H \approx 4.5$. Next-generation extreme adaptive optics systems on ground-based 8 m class telescopes like the Gemini Planet Imager 2.0 (J. Chilcote et al. 2022) operating in ideal conditions will be able to achieve H -band contrasts of 10^7 at separations of $0''.2$. According to the Sonora grid of evolutionary models presented in M. S. Marley et al. (2021), a 400 Myr old $M_p \approx 10 M_{\text{Jup}}$ planet will have $H \approx 23$. At a distance of 90 pc orbiting a $M_* \approx 3 M_\odot$ star at semimajor axis $a \approx 10$ au close to the peak of the occurrence of such objects orbiting $M_* \approx 2 M_\odot$ stars (e.g., E. L. Nielsen et al. 2019; V. Wothoff et al. 2022), an H -band direct imaging detection of that planet would require a contrast of 10^{10} at less than $0''.2$.

As a consequence, even next-generation ground-based instruments will be insensitive to planet-mass objects orbiting massive stars at the separations where theoretical predictions plus long-term Doppler monitoring and direct imaging observations of $M_* \approx 2 M_\odot$ stars suggest they should be present (e.g., S. Reffert et al. 2015; E. L. Nielsen et al. 2019; V. Wothoff et al. 2022). Gaia astrometry will also be insensitive to giant planets orbiting stars with $M_* \gtrsim 3 M_\odot$, as the few nearby stars in this mass range saturate Gaia’s detectors and make the most precise astrometric measurements impossible. For all of these reasons, only a few objects in the NASA Exoplanet Archive (R. L. Akeson et al. 2013) orbit stars with $M_* \gtrsim 3 M_\odot$ (e.g., M. Janson et al. 2019; T.-Y. Bang et al. 2020; V. Squicciarini et al. 2022). Though not listed in the NASA Exoplanet Archive, the B-star Exoplanet Abundance Study has also found objects those authors refer to as planets (M. Janson et al. 2021a, 2021b). None of these few objects have $M \lesssim 10 M_{\text{Jup}}$ and $a \approx 10$ au as expected for objects frequently formed via core-accretion for stars in this mass range near their parent protoplanetary disks’ water-ice lines (G. M. Kennedy & S. J. Kenyon 2008).

While this population of giant planets predicted to frequently orbit stars with initial mass $M_{*,i} \gtrsim 3 M_\odot$ (i.e., main-sequence B stars) at $a \approx 10$ au is difficult to characterize while fusion persists in their host stars, the population can be studied with the direct imaging technique once their hosts become massive, young white dwarfs (M. R. Burleigh et al. 2008; E. Hogan et al. 2009, 2010, 2011; S. Xu et al. 2015; W. Brandner et al. 2021). Despite the fact that young white dwarfs are hot, their radii would be an order of magnitude smaller than the radii of any equally young giant planet-mass objects that might be present. In that situation, depicted in Figure 1, as a consequence of an opacity minimum in young giant planet-mass objects’ cloudless atmospheres, such objects would be observable as significant infrared excesses at $4.5 \mu\text{m}$

with only the expected fluxes from the host white dwarf’s photosphere at 3.6 or $5.8 \mu\text{m}$ (e.g., A. Burrows et al. 1997; M. R. Burleigh et al. 2002; A. Gould & M. Kilic 2008; M. S. Marley et al. 2021). Excess flux above the expected contribution from the white dwarf’s photosphere at $4.5 \mu\text{m}$ combined with a lack of excess flux at 3.6 and $5.8 \mu\text{m}$ is difficult to reproduce with unresolved emission from a disk of dust or contamination by a background galaxy. This signature is consequently an excellent way to identify candidate giant planets orbiting massive, young white dwarfs that were B stars on the main sequence.

Although previous searches for Spitzer Infrared Array Camera (IRAC) unresolved mid-infrared excess indicative of the presence of giant planets orbiting solar-neighborhood white dwarfs produced nondetections (e.g., F. Mullally et al. 2007; J. Farihi et al. 2008; M. Kilic et al. 2009), the unprecedented resolution and photometric precision of the James Webb Space Telescope (JWST) Mid-Infrared Instrument have recently enabled the discovery of resolved giant planet candidates orbiting both nearby white dwarfs and white dwarfs with metal-enriched photospheres (M. A. Limbach et al. 2024; S. E. Mullally et al. 2024).

In this article, we describe a search for unresolved infrared excess in a sample of 51 massive, young white dwarfs with homogeneously reduced archival Spitzer/IRAC [3.6] and [4.5] photometry. These data provide sensitivity to giant planet-mass objects with $M \lesssim 10 M_{\text{Jup}}$ for 30 white dwarfs. In this sample, we identify one candidate giant planet in the Galaxy Evolution Explorer (GALEX) J071816.4+373139 white dwarf system and infer the occurrence of giant planets orbiting main-sequence B stars with $M_{*,i} \gtrsim 3 M_\odot$. We outline the construction of our sample and its analysis in Section 2. We then focus on the properties of the giant planet candidate in the GALEX J071816.4+373139 system in Section 3 and the inference of η_{GP} in Section 4. We conclude by summarizing our results in Section 5.

2. Data and Analysis

2.1. Gaia-based Selection of Massive, Young White Dwarfs

We use the publicly available `WD_models` code (S. Cheng 2025)⁵ described in detail in S. Cheng et al. (2019) to construct a solar-neighborhood sample of massive, young white dwarfs suitable for the detection of unresolved giant planets using Spitzer/IRAC photometry. We first infer effective temperatures T_{eff} by fitting an interpolated grid of synthetic photometry predicted to be produced by both DA (hydrogen-rich) and DB (helium-rich) white dwarf model atmospheres (J. B. Holberg & P. Bergeron 2006; P. M. Kowalski & D. Saumon 2006; P. Bergeron et al. 2011; P. E. Tremblay et al. 2011; S. Blouin et al. 2018) to observed Gaia EDR3 $G_{\text{BP}} - G_{\text{RP}}$ colors and M_G absolute magnitudes (Gaia Collaboration et al. 2016, 2021a; C. Fabricius et al. 2021; M. Riello et al. 2021; N. Rowell et al. 2021; F. Torra et al. 2021). With T_{eff} in hand, we then infer white dwarf radii using observed fluxes, Gaia EDR3 parallax-based distance inferences (L. Lindegren et al. 2021a, 2021b), and the Stefan–Boltzmann law. Assuming that the white dwarfs in our sample were the result of the evolution of single stars, we next use the white dwarf cooling models presented in A. Bédard et al. (2020) to infer white dwarf masses M_{WD} and cooling ages

⁵ https://github.com/SihaoCheng/WD_models

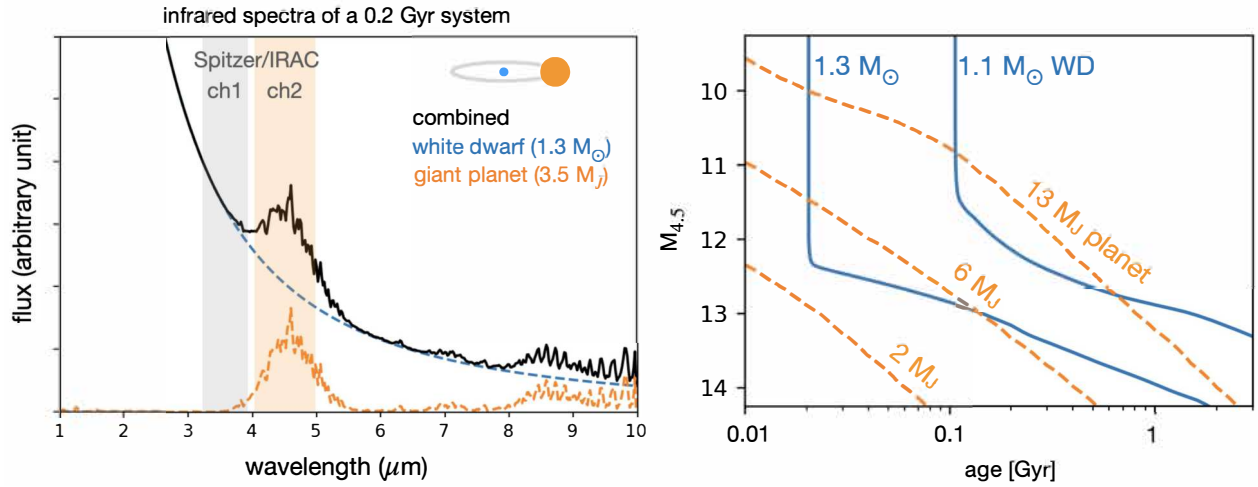


Figure 1. Left: composite spectrum of a typical young white dwarf plus young giant planet system. Right: absolute magnitude $M_{4.5}$ in the Spitzer Infrared Array Camera (IRAC) 4.5 μm Channel 2 band as a function of time for both massive white dwarfs and giant planets. Planet-mass objects with clear atmospheres are therefore observable for at least a few tens of Myr after their host stars become white dwarfs.

τ_{cool} . We finally calculate white dwarf total ages $\tau = \tau_* + \tau_{\text{cool}}$ based on the J. D. Cummings et al. (2018) zero-age main sequence to white dwarf initial-final mass relation. While the assumption of single stellar evolution and modeling uncertainties are inherent in this approach, the white dwarf cooling models we use are well calibrated and in accord with other white dwarf cooling models (M. Salaris et al. 2013). Since age inference uncertainties for massive white dwarfs are dominated by cooling age uncertainties, the system ages we subsequently use in our sample selection and search for unresolved giant planets should be robust.

We apply the procedure described above to Gaia EDR3 objects identified as white dwarfs by N. P. Gentile Fusillo et al. (2019). In particular, we select objects with $\tau < 1.2$ Gyr, $M_{\text{WD}} > 0.7 M_{\odot}$, and $d = 1/\pi < 200$ pc. This procedure leads to the sample of 2195 massive, young white dwarfs in the solar neighborhood illustrated in Figure 2.

2.2. Spitzer/IRAC Analysis of Our White Dwarf Sample

To search for the infrared excess characteristic of unresolved giant planets orbiting our white dwarf sample, we crossmatch our sample with the Spitzer Enhanced Imaging Products (SEIP) Source List (IRSA & SSC 2020) available from the NASA/IPAC Infrared Science Archive (IRSA). The SEIP Source List includes homogeneous photometric measurements for all pointlike sources in areas of the sky observed from 2003 to 2009 during Spitzer’s cryogenic phase. We account for the proper motions of the white dwarfs in our catalog by first converting the epoch 2016.5 Gaia EDR3 right ascensions and declinations to the mean epoch of the Spitzer cryogenic phase 2006.0. We then match the white dwarfs in our catalog with the nearest SEIP Source List object within $1''.5$.

This procedure results in the 65 matches with IRAC photometry illustrated in Figure 2, 51 with both [3.6] and [4.5] plus 14 with only [4.5]. Of these 65 matches, 57 were observed by white dwarf-focused programs and have been previously studied (F. Mullally et al. 2007; J. Farihi et al. 2008; M. Kilic et al. 2009; S. D. Barber et al. 2016). The other eight were serendipitously observed by Spitzer programs that were not focused on white dwarfs. While a larger absolute

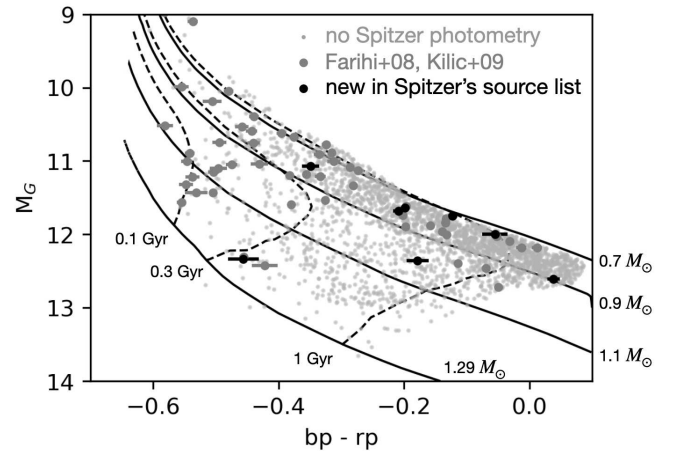


Figure 2. HR diagram of massive, young white dwarfs in our sample. We plot our sample of 2195 white dwarfs as the smaller gray points. We plot as larger gray points white dwarfs that were searched for the infrared excess characteristic of unresolved giant planets by J. Farihi et al. (2008) or M. Kilic et al. (2009). We plot as black points white dwarfs in our sample with SEIP Source List photometry searched for the infrared excess characteristic of unresolved giant planets for the first time in this article. We plot as yellow curves cooling tracks for DA white dwarfs with $M_{\text{WD}} = (0.7, 0.9, 1.1, 1.29) M_{\odot}$.

number of white dwarfs were studied by T. G. Wilson et al. (2019) using data from Spitzer’s warm phase (Programs 80149 and 12103), only one of our massive, young white dwarfs, WD 1134+300, was included in that study. We note that even for white dwarfs studied previously, SEIP Source List photometry provides better accuracy and higher precision than previous studies due to its production by the most up-to-date pipeline using the best zero-point and photometric corrections calibrated with all Spitzer cryogenic data available.⁶ In particular, as we will describe in detail in Section 2.3, these SEIP Source List data warrant a reanalysis because residual χ^2 values suggest that published analyses of these same Spitzer data likely overestimated photometric uncertainties.

⁶ https://irsa.ipac.caltech.edu/data/SPITZER/Enhanced/SEIP/docs/seip_explanatory_supplement_v3.pdf

Unlike the data sets produced by the Wide-field Infrared Explorer (WISE; E. L. Wright et al. 2010), the Spitzer SEIP Source List is not an all-sky catalog. Nevertheless, Spitzer’s superior sensitivity and angular resolution relative to WISE makes the SEIP Source List a better data set to use for a search for the infrared excess characteristic of unresolved giant planets. Indeed, we also explored the possibility of using CatWISE2020 W1 and W2 photometry (A. Mainzer et al. 2011; P. R. M. Eisenhardt et al. 2020; F. Marocco et al. 2021) as an all-sky supplement to the more precise Spitzer SEIP Source List photometry. Like other groups (e.g., E. Dennihy et al. 2017; S. Xu et al. 2020; S. Lai et al. 2021), we found that even after removing from consideration objects with UK Infra-Red Telescope (UKIRT) Hemisphere Survey (S. Dye et al. 2018) or Visible and Infrared Survey Telescope for Astronomy (VISTA) Hemisphere Survey (R. G. McMahon et al. 2013) J -band excesses, a large number of white dwarfs with apparent CatWISE2020 infrared excess could still be attributed to infrared-bright galaxies with very faint near-infrared counterparts. This increased incidence of confusion relative to the Spitzer SEIP Source List is a consequence of WISE’s coarser spatial resolution and lower sensitivity. We ultimately concluded that CatWISE2020 is unsuitable for a search for the infrared excess characteristic of unresolved giant planets.

2.3. Color and 4.5 μm Flux Excesses

To quantify the statistical significance of any excess flux in the mid-infrared beyond the expected contribution from the white dwarf photosphere, we define the flux and color excesses as

$$\text{flux excess} = m_{\text{model}}(M_G, G_{\text{BP}} - G_{\text{RP}}) - m_{\text{obs}} + \delta_m, \quad (1)$$

$$\text{color excess} = C_{\text{obs}} - C_{\text{model}}(M_G, G_{\text{BP}} - G_{\text{RP}}) + \delta_C. \quad (2)$$

Here m refers to an apparent magnitude and C refers to the quantity $m_{[3.6]} - m_{[4.5]}$ assuming a $3''.8$ aperture. δ_m and δ_C represent the approximately 1.5% systematic uncertainties of Spitzer’s absolute photometric calibration. The presence of an unresolved giant planet would manifest as a flux excess at 4.5 μm but not at 3.6 μm . On the other hand, a dust disk or background galaxy would be expected to produce excesses at both 3.6 and 4.5 μm . To make optimal use of the available photometric data and thereby obtain the best sensitivity to unresolved giant planets, we focus on color excess between the two bands as a relative quantity with lower uncertainty instead of excesses in individual fluxes.

The flux and color excess uncertainties have contributions from both the input photometry itself and white dwarf model parameter uncertainties

$$\sigma(\text{flux excess}) = \sqrt{\sigma_{\text{obs}}^2 + \sigma_{\text{model}}^2 + \sigma_{\text{extra}}^2}, \quad (3)$$

$$\sigma(\text{color excess}) = \sqrt{\sigma_{\text{obs},3.6}^2 + \sigma_{\text{obs},4.5}^2 + \sigma_{\text{color,model}}^2 + \sigma_{\text{color,extra}}^2}. \quad (4)$$

The advantage of color excess is that (1) its model error is almost zero because parallax errors cancel out between the two bands and (2) for hot white dwarfs, color is not sensitive to temperature. This latter point is a consequence of the fact that in this case Spitzer data only cover the Rayleigh–Jeans tail of each white dwarf’s spectral energy distribution that has a color index close to zero. In contrast, flux excess as an absolute

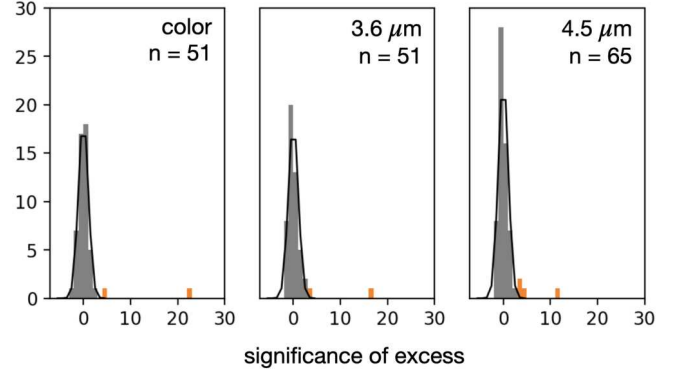


Figure 3. Histograms of infrared excess significances. Note that cores of each distribution match well with a standard Gaussian profile plotted in black. We indicate individual white dwarfs with excesses beyond 3σ in orange.

photometric quantity has a higher uncertainty as a consequence of photometric uncertainty, parallax uncertainty, white dwarf temperature estimate uncertainty, and possibly extinction and its uncertainty.⁷ We therefore use color excess for the selection of giant planet candidates and only use flux excess for the exclusion of possible contamination. We note that the nominal uncertainty of aperture photometry in the SEIP Source List is underestimated by a factor of 2, so we set σ_{obs} to be 2 times the nominal photometric uncertainty for the $3.8''$ aperture in the SEIP Source List.

We also add an extra uncertainty term to include other sources of uncertainties, such as the intrapixel variation of IRAC photometry. We note that similar published analyses tend to overestimate color excess uncertainties, as indicated by the fact that their dispersions of color excess significance $\Sigma = \text{color excess}/\sigma(\text{color excess})$ are smaller than unity: 0.8 in T. G. Wilson et al. (2019) and 0.6 in S. Lai et al. (2021). Overly conservative uncertainties are not problems for searches for large infrared excesses due to disks or brown dwarfs that are bright and tend to produce strong signals. However, an overly conservative uncertainty would significantly reduce the constraining power of a planet search. We find that $\sigma_{\text{color,extra}} = 3\%$ and $\delta_C = -0.7\%$ lead to a zero mean and unity dispersion in Σ after clipping 3σ outliers. Similarly, for the flux excesses $\sigma_{3.6,\text{extra}} = 5\%$, $\delta_{3.6} = -1.5\%$, $\sigma_{4.5,\text{extra}} = 4\%$, and $\delta_{4.5} = -0.8\%$ yield zero means and unity dispersions for $\chi = \text{flux excess}/\sigma(\text{flux excess})$. These values are consistent with the values used in the literature (e.g., J. Farihi et al. 2008; T. G. Wilson et al. 2019; S. Lai et al. 2021).

We plot in Figure 3 histograms of Σ , $\chi_{3.6}$, and $\chi_{4.5}$, which show core profiles that are consistent with standard Gaussian distributions with (mean, standard deviation) ordered pairs (0.02, 0.98), (0.01, 1.02), and (−0.01, 1.01). As a cross validation of our approach to color and flux excesses, we also examined another sample of 379 white dwarfs in the SEIP Source List that are not part of our science sample. After

⁷ According to the formula for error propagation

$$\sigma_{\text{model}} = \sqrt{(\sigma_{M_G} \cdot \partial_{M_G} m_{\text{model}})^2 + (\sigma_{G_{\text{BP}} - G_{\text{RP}}} \cdot \partial_{G_{\text{BP}} - G_{\text{RP}}} m_{\text{model}})^2}, \quad (5)$$

$$\approx \sqrt{\left(\frac{2.17\sigma_w}{\omega}\right)^2 + \sigma_G^2 + (\sigma_{G_{\text{BP}} - G_{\text{RP}}} \cdot \partial_{G_{\text{BP}} - G_{\text{RP}}} m_{\text{model}})^2}. \quad (6)$$

Table 1
White Dwarfs with Color Excess Larger than 2σ

| White Dwarf | Gaia EDR3 <i>source_id</i> | Σ | $\chi_{3.6}$ | $\chi_{4.5}$ |
|-------------|----------------------------|----------|--------------|--------------|
| 0003+4336 | 384841336150015360 | 2.1 | -1.1 | 1.3 |
| 0148+1902 | 95297185335797120 | 22.4 | 52.7 | 120.6 |
| 0718+3731 | 898348313253395968 | 4.3 | -1.1 | 3.1 |

Note. Most are consistent with a blackbody origin. We flag as candidates only white dwarfs with 3σ significant flux excess at $4.5\ \mu\text{m}$ with both (1) no statistically significant flux excess at $3.6\ \mu\text{m}$ and (2) an absolute flux excess at $3.6\ \mu\text{m}$ less than 0.5 mag. Among the 51 objects in our sample for which these inferences are possible, only WD 0718+3731 has a statistically significant color and flux excess consistent with a giant planet origin.

removing objects with large (30%) $4.5\ \mu\text{m}$ flux excesses, the color excess significance Σ has $(-0.00, 1.04)$. This result further validates the photometric reliability of the SEIP Source List and our color excess uncertainty model. It also shows that our approach is applicable to other Spitzer observations. On the other hand, as argued above, the flux excess is not as stable, as it has $(0.09, 1.15)$ and $(0.11, 1.13)$ in [3.6] and [4.5].

We report in Table 1 the white dwarfs in our sample with statistically significant color and flux excesses. We also provide a complete list of the 51 white dwarfs in our sample in the Appendix. If we further require both (1) no statistically significant [3.6] flux excess and (2) an absolute [3.6] excess less than 0.5 mag, then two candidates remain: WD 0003+4336 and WD 0718+3731 with color excesses significant at the 2.1σ and 4.3σ levels. At our inferred total ages for these white dwarfs, their observed excesses could be produced by giant planets with $M_p = 4.9 M_{\text{Jup}}$ and $M_p = 3.6 M_{\text{Jup}}$. However, we expect that in our sample of 51 white dwarfs one will have a color excess significant at the 2σ level due to chance alone. Indeed, we also find one object with a color deficiency (rather than excess) significant at the 2.4σ level, confirming the fidelity of our uncertainty estimates. The probability of identifying a white dwarf with a color excess significant at the 4.3σ level due to randomness is extremely low (0.001 for a sample of size 51). As a result, we conclude that the color excess we observe in the WD 0718+3731 system is astrophysical in origin and best explained by the presence of an unresolved giant planet. On the other hand, we attribute the color excess we observe in the WD 0003+4336 system to randomness. We give in Table 2 the properties of the candidate giant planet in the WD 0718+3731 system if its color and flux excesses are interpreted as a consequence of the presence of an unresolved giant planet companion.

Our color and flux excess criteria give us sensitivity to objects with $M \gtrsim 6 M_{\text{Jup}}$ for white dwarfs with $M_{\text{WD}} \approx 0.7 M_{\odot}$ and sensitivity to objects with $M \gtrsim 2 M_{\text{Jup}}$ for white dwarfs with $M_{\text{WD}} \approx 1.4 M_{\odot}$. Our requirement that the absolute [3.6] flux excess be less than 0.5 mag allows us to differentiate between unresolved dust disks and giant planet-mass objects at the cost of sensitivity to brown dwarfs. For white dwarfs with $M_{\text{WD}} \approx 0.7 M_{\odot}$, we are insensitive to brown dwarfs with $M \gtrsim 50 M_{\text{Jup}}$. For white dwarfs with $M_{\text{WD}} \approx 1.4 M_{\odot}$, we are insensitive to brown dwarfs with $M \gtrsim 10 M_{\text{Jup}}$.

3. A Candidate Giant Planet in the GALEX J071816.4+373139 System

The white dwarf WD 0718+3731, referred to by its Simbad designation GALEX J071816.4+373139 hereafter, has a [3.6]–

[4.5] color excess significant at the 4.3σ level, a [4.5] flux excess significant at the 3.1σ level, and no significant [3.6], [5.8], or [8.0] flux excesses. We emphasize that the significances of these excesses are independent of any white dwarf model. If we use the total age for the white dwarf $\tau = 0.2$ Gyr inferred using the methodology described in Section 2, a white dwarf model atmosphere with its T_{eff} , and the cloudless models for giant planets and brown dwarfs published by M. S. Marley et al. (2021), then the [3.6]–[4.5] color excess we observe for GALEX J071816.4+373139 can be used to infer the mass of a potential unresolved giant planet-mass object responsible for the color excess. We find that all of our observations and inferences for the GALEX J071816.4+373139 system can be self-consistently explained by the presence of an unresolved giant planet-mass object with $M_p \approx 3.6 M_{\text{Jup}}$ and the properties given in Table 2.

It is possible that the [4.5] flux excess we observe in the GALEX J071816.4+373139 system could be explained by a dust disk. A disk of dust with $T_{\text{dust}} \approx 650$ K could produce a [4.5] flux excess, but it would be unlikely to produce the color excess we observe. In any case, such a dust disk would produce significant [5.8] and [8.0] flux excesses that we do not observe. We therefore argue that a dust disk with $T_{\text{dust}} \approx 650$ K is inconsistent with our observations of the GALEX J071816.4+373139 system.

An unresolved optically faint but mid-infrared bright background high-redshift star-forming galaxy with strong emission lines could conceivably produce the [3.6]–[4.5] color excess, the [4.5] flux excess, and nondetections of [3.6], [5.8], and [8.0] flux excesses we observe in the GALEX J071816.4+373139 system. To investigate the likelihood of this scenario, we use archival Spitzer/IRAC data in the COSMOS field (D. B. Sanders et al. 2007) to quantify the density on sky of background galaxies that could create a similar observational signature to what we observe in the GALEX J071816.4+373139 system. We find that a chance alignment with a background galaxy that could create a similar color excess has only a 0.005 (i.e., 1 in 200) chance of producing an event like that we observe in the GALEX J071816.4+373139 system in our 51-star sample. We note that GALEX J071816.4+373139 lies in projection about 1° from the core of the galaxy cluster MACS J0717.5+3745. Indeed, the Spitzer data we use in our analysis were collected by Program 40652 studying that cluster. The cluster has $z = 0.546$, so any star-forming galaxies with strong emission lines in that cluster would be visible in existing optical and near-infrared data at the location of GALEX J071816.4+373139. We therefore argue that an optically faint but mid-infrared bright background high-redshift star-forming galaxy with strong emission lines is unlikely to explain all of our observations for the GALEX J071816.4+373139 system.

GALEX J071816.4+373139 is very massive: $M_{\text{WD}} = 1.27 M_{\odot}$ assuming the oxygen–neon white dwarf model from M. E. Camisassa et al. (2019) or $M_{\text{WD}} = 1.29 M_{\odot}$ assuming the carbon–oxygen white dwarf model from A. Bédard et al. (2020). GALEX J071816.4+373139 is therefore among the most massive white dwarfs in the solar neighborhood (M. Kilic et al. 2021). Assuming GALEX J071816.4+373139 was the result of single stellar evolution, then its progenitor had an initial mass in the range $6 M_{\odot} \lesssim M_{*,i} \lesssim 10 M_{\odot}$ with the value dependent on the specific J. D. Cummings et al. (2018) initial–final mass relation adopted. As a consequence, the giant planet candidate in the GALEX

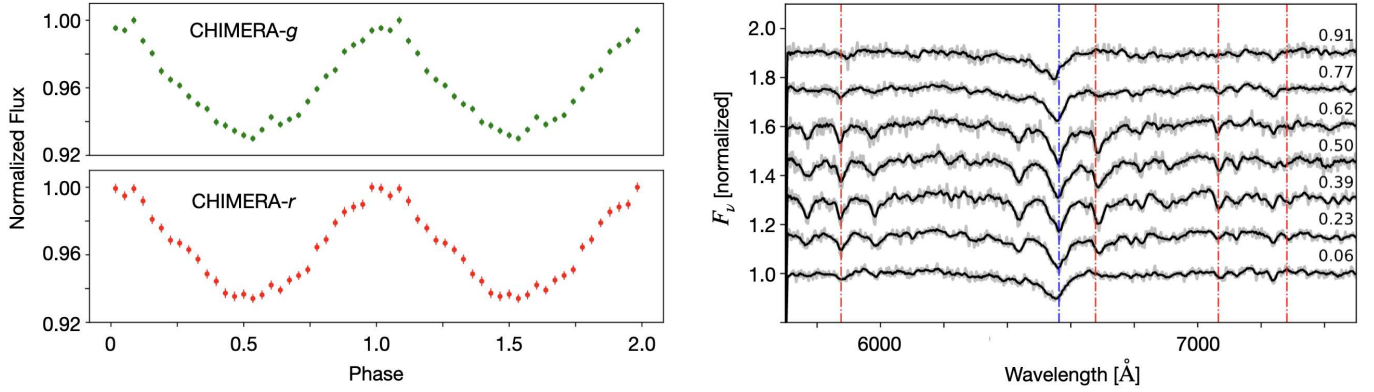


Figure 4. Time-resolved photometric and spectroscopic observations of GALEX J071816.4+373139. Top left: phase-folded g' light curve from the high-speed imaging photometer CHIMERA on the 5 m Hale Telescope (L. K. Harding et al. 2016). Bottom left: phase-folded r' CHIMERA light curve. GALEX J071816.4+373139 varies by about 6% peak-to-peak with a period of 11.3 minutes. Right: phase-resolved Keck/LRIS spectra of GALEX J071816.4+373139 normalized and shifted vertically for clarity with the numbers on the right side of the plot indicating the center of each phase bin. Phase 0 corresponds to the maximum in the light curve illustrated on the left. The blue vertical line highlights hydrogen $H\alpha$ while the red lines indicate absorption lines of neutral helium. At phase 0.5, $H\alpha$ and the helium 5875 Å line are almost equally strong, and their Zeeman splitting implies a magnetic field with $|B| \approx 8$ MG. At phase 0, only hydrogen is present and the absence of splitting indicates $|B| \lesssim 1$ MG.

Table 2
Properties of Our Candidate White Dwarf–Unresolved Giant Planet System

| White Dwarf | Gaia EDR3 source_id | d (pc) | τ (Gyr) | M_{WD} (M_{\odot}) | $M_{*,i}$ (M_{\odot}) | M_p (M_{Jup}) | $T_{eff,p}$ (K) | $\log g$ | [3.6] Flux (μJy) | [4.5] Flux (μJy) | [4.5] Flux Excess (μJy) |
|-------------|------------------------|-------------|-----------------|-----------------------------|------------------------------|------------------------|--------------------|----------|----------------------------|----------------------------|-----------------------------------|
| 0718+3731 | 898348313253395968 | 85 | 0.2 | 1.37 | 8 | 3.6 | 400 | 3.8 | 16.5 ± 0.6 | 15.5 ± 0.7 | 4.9 ± 0.8 |

J071816.4+373139 system would have formed around the most massive star known to have hosted a planet while it was on the main sequence.

Our mass inference for the giant planet-mass object in the GALEX J071816.4+373139 system relies on our inferred total age for GALEX J071816.4+373139, which assumes that the white dwarf was the result of single stellar evolution. If the white dwarf GALEX J071816.4+373139 was formed through the merger of two lower-mass white dwarfs, then those white dwarfs would have had much longer main-sequence lifetimes. The total age for the system would then be much longer than we inferred, and the mass of the unresolved object responsible for the color and flux excesses would be much more massive, almost certainly a brown dwarf. In that case, because both the two now-merged white dwarfs would have had main-sequence masses well below the mass of a main-sequence B star, the GALEX J071816.4+373139 system would not be useful to constrain the occurrence of giant planets orbiting massive main-sequence stars. GALEX J071816.4+373139 is known to be photometrically variable (left panels of Figure 4), and this variability has been attributed to the rotation of an inhomogeneous surface created by a strong magnetic field sometimes predicted to be found in massive white dwarfs formed via mergers.

If the massive white dwarf GALEX J071816.4+373139 was the result of a merger between two lower-mass white dwarfs and therefore old, then it would be expected to have “hot” Galactic kinematics observable as a high tangential velocity (S. Cheng et al. 2020) in addition to a strong magnetic field and fast rotation (M. Kilic et al. 2023). The tangential velocity of GALEX J071816.4+373139 with respect to the local standard of rest is about 10 km s^{-1} . Assuming the J. Holmberg et al. (2009) age–velocity dispersion relation for the Milky

Way’s disk, the age implied by this transverse velocity is consistent with the our single stellar evolution-based age inference, thereby supporting our mass inference for the unresolved object in the GALEX J071816.4+373139 system. Likewise, while GALEX J071816.4+373139 is thought to have a strong magnetic field, it is still debated whether all strong magnetized and fast rotating white dwarfs are produced by mergers (L. Ferrario et al. 2015).

In addition to its photometric variability, GALEX J071816.4+373139 is spectroscopically variable as well. Time-resolved Keck/Low-Resolution Imaging Spectrometer (LRIS) data have revealed that GALEX J071816.4+373139 is “two faced,” with one hemisphere hydrogen dominated and the other helium dominated (right panel of Figure 4). As argued by I. Caiazzo et al. (2023), this two-faced nature is likely the result of inhomogeneous surface magnetic fields that result in temperature, pressure, or mixing strength variation over the surface. I. Caiazzo et al. (2023) suggested that as GALEX J071816.4+373139 cools it is undergoing a transition from a hydrogen-dominated to a helium-dominated atmosphere. The strength of GALEX J071816.4+373139’s magnetic field could generate cyclotron emission that could produce a [4.5] flux excess. Like the dust disk scenario, the power-law nature of cyclotron emission that produces a [4.5] flux excess would also likely produce [3.6], [5.8], and [8.0] flux excesses that we do not observe. Cyclotron emission would also require ongoing accretion, and as described above, our analysis rules out the presence of a brown-dwarf mass companion to GALEX J071816.4+373139. We therefore argue that power-law cyclotron emission as a consequence of ongoing accretion is inconsistent with our observations of the GALEX J071816.4+373139 system.

Our mass inferences for the unresolved companion in the GALEX J071816.4+373139 system responsible for the

Table 3
Occurrence as a Function of Candidate Giant-planet/Brown-dwarf Mass

| Mass Range | Sample Size Uncorrected for Mergers | Sample Size Corrected for Mergers | Number of Candidates | Occurrence |
|---|--|--------------------------------------|-------------------------|------------------------|
| $3 M_{\text{Jup}} < M_p < 10 M_{\text{Jup}}$ | 12 | 9 | 1 | $0.11^{+0.13}_{-0.07}$ |
| $5 M_{\text{Jup}} < M_p < 10 M_{\text{Jup}}$ | 30 | 23 | 0 | <0.0099 |
| $10 M_{\text{Jup}} < M_p < 20 M_{\text{Jup}}$ | 29 | 22 | 0 | <0.010 |
| $10 M_{\text{Jup}} < M_p < 30 M_{\text{Jup}}$ | 26 | 20 | 0 | <0.011 |

Note. We note that if GALEX J071816.4+373139 did form as the result of a merger between two lower-mass white dwarfs, then our inference of the occurrence of objects with $3 M_{\text{Jup}} < M_p < 10 M_{\text{Jup}}$ orbiting main-sequence B stars would be $\eta_{\text{GP}} < 0.025$ (i.e., an upper limit with the value 0.025).

[3.6]–[4.5] color and [4.5] flux excesses we observe relies on the M. S. Marley et al. (2021) grid of evolution and atmosphere models for brown dwarfs and giant planets. Those models assume cloudless atmospheres that are likely appropriate for our inferred temperature of the unresolved companion in the GALEX J071816.4+373139 system. Nevertheless, if the unresolved companion in the GALEX J071816.4+373139 system is cloudy, then its mass would be somewhat larger than the $M_p \approx 3.6 M_{\text{Jup}}$ we infer based on our observed color excess using the cloudless M. S. Marley et al. (2021) models. In addition, nonequilibrium chemistry resulting from vertical mixing may reduce the $4.5 \mu\text{m}$ flux of giant planet-mass objects by about 50% (e.g., M. W. Phillips et al. 2020). Our mass estimate for the unresolved companion in the GALEX J071816.4+373139 system is therefore likely a lower limit.

4. The Occurrence of Giant Planets Orbiting B Stars

In addition to the identification of an unresolved giant planet candidate in the GALEX J071816.4+373139 system, our nondetections of color excesses attributable to unresolved giant planets or brown dwarfs in our sample of young, massive white dwarfs also enable us to infer the occurrence of giant planets orbiting stars with $M_{*,i} \gtrsim 3 M_{\odot}$. In addition to our detection of a planet candidate with $M_p \approx 3.6 M_{\text{Jup}}$, our occurrence inference depends on the number of white dwarfs with sufficiently precise Spitzer/IRAC photometry in the SEIP Source List to enable the detection of planet-mass objects. We define our effective sample size $N_{\text{WD}}(M_p)$ as a function of planet mass as the number of white dwarfs for which a planet of mass M_p would produce a 2σ color excess detection.

Since some of the massive, apparently young white dwarfs in our sample will be the result of mergers between two lower-mass white dwarfs and therefore much older than suggested by our analyses that assumed single stellar evolution, we must also correct N_{WD} for this merger fraction. S. Cheng et al. (2020) showed that about 25% of massive white dwarfs in the solar neighborhood are the result of mergers, so we multiply N_{WD} by 0.75 to account for these merger products.

We model the number of giant planet/brown dwarf candidates N_{cand} in a sample of size N_{WD} candidates using a binomial distribution. Following K. C. Schlafman (2014), we exploit the fact that a Beta(α, β) distribution is a conjugate prior to the binomial distribution and will result in a Beta distribution posterior for the occurrence of giant planet/brown dwarf candidates in a sample. Bayes’s theorem guarantees

$$f(\theta|\mathbf{y}) = \frac{f(\mathbf{y}|\theta)f(\theta)}{\int f(\mathbf{y}|\theta)f(\theta)d\theta}, \quad (7)$$

where $f(\theta|\mathbf{y})$ is the posterior distribution of the model parameter θ , $f(\mathbf{y}|\theta)$ is the likelihood of the data \mathbf{y} given θ , and $f(\theta)$ is the prior for θ . In this case, the likelihood is the binomial likelihood that describes the probability of a number of successes y in n Bernoulli trials, each with probability θ of success:

$$f(y|\theta) = \binom{n}{y} \theta^y (1 - \theta)^{n-y}. \quad (8)$$

As shown by K. C. Schlafman (2014), in this situation using a Beta(α, β) prior on θ with hyperparameters α and β results in a Beta posterior for θ of the form Beta($\alpha + N_{\text{cand}}, \beta + N_{\text{WD}} - N_{\text{cand}}$).

The hyperparameters α and β of the prior can be thought of as encoding a certain amount of prior information in the form of pseudo-observations. Specifically, $\alpha - 1$ is the number of successes and $\beta - 1$ is the number of failures imagined to have already been observed and therefore included as prior information on θ . Taking any $\alpha = \beta = i$ where $i \geq 1$ could be thought of as an uninformative prior in the sense that the probabilities of success and failure in the prior distribution are equally likely. However, if i is large, then there is imagined to be a lot of prior information, and the posterior distribution will mostly reflect the prior when $n \leq i$. On the other hand, if $n \gg i$, then the posterior will be dominated by the data. Since in our case both N_{cand} and N_{WD} are small, when $N_{\text{cand}} > 0$ we choose the improper prior $\alpha = \beta = 0.3$ such that our posterior median is equal to $N_{\text{cand}}/N_{\text{WD}}$. We then use the same $\alpha = \beta = 0.3$ when $N_{\text{cand}} = 0$ and quote as upper limits the upper boundaries of credible intervals containing 68% of the occurrence posteriors.

We give in Table 3 $N_{\text{WD}}(M_p)$ both uncorrected for and corrected for mergers as well as our overall occurrence inferences. We plot in Figure 5 occurrence as a function of host stellar mass converted from white dwarf mass using the open cluster-based J. D. Cummings et al. (2018) initial–final mass relation. To convert the planet occurrence around white dwarfs into that around the progenitor stars, we account for planet survival and orbital migration. When a star evolves into a white dwarf, shedding several solar masses into space, planetary orbits expand stably and adiabatically by a factor proportional to the initial–final mass ratio of the host star (D. Veras et al. 2011, 2020). Planets with small orbital separations will be tidally engulfed during the giant phase, but planets on wider orbits are expected to survive. A. J. Mustill & E. Villaver (2012) suggest minimum initial orbit radii $4 \text{ au} \lesssim a \lesssim 7 \text{ au}$ and final orbit radii $8 \text{ au} \lesssim a \lesssim 20 \text{ au}$ for stars with $3 M_{\odot} \lesssim M_{*,i} \lesssim 9 M_{\odot}$ (i.e., $0.7 M_{\odot} \lesssim M_{\text{WD}} \lesssim 1.4 M_{\odot}$). Therefore, the occurrence we

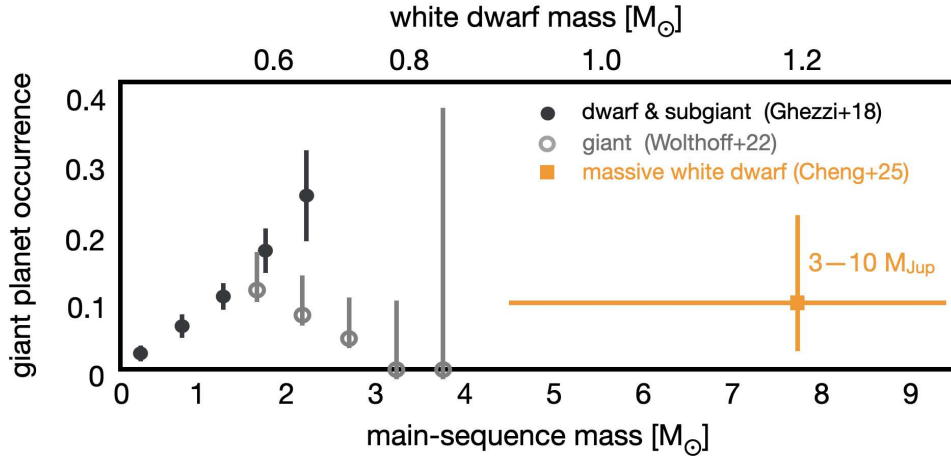


Figure 5. Dependence of giant planet occurrence on host star mass.

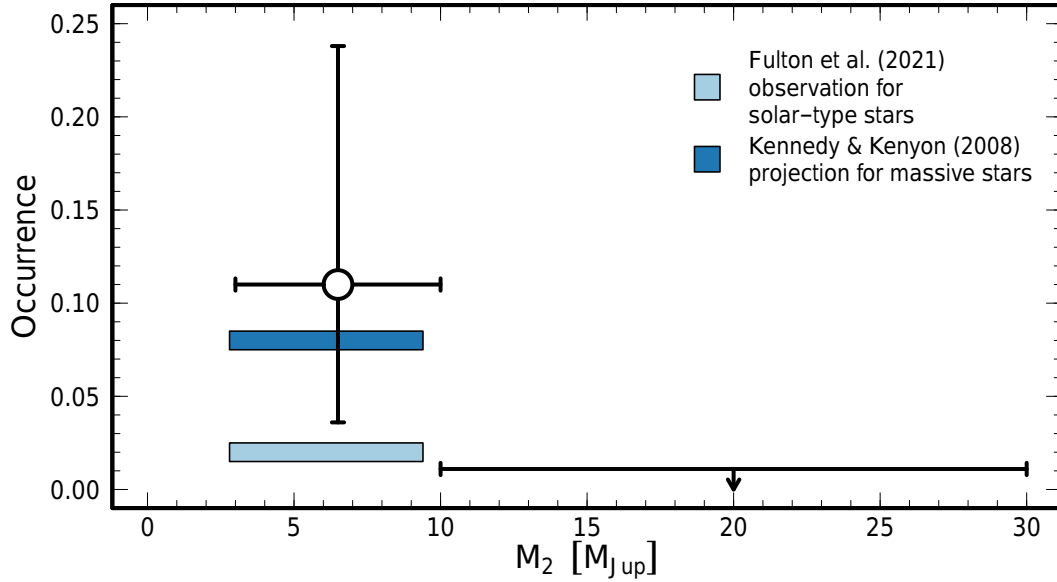


Figure 6. Occurrence of giant planets and brown dwarfs as function of mass. For stars with $M_{*,i} \gtrsim 3 M_{\odot}$, we find $\eta_{\text{GP}} = 0.11^{+0.13}_{-0.07}$ in the mass range $3 M_{\text{Jup}} \lesssim M_p \lesssim 10 M_{\text{Jup}}$, and $\eta_{\text{BD}} < 0.011$ in the mass range $10 M_{\text{Jup}} \lesssim M_p \lesssim 30 M_{\text{Jup}}$. The former value is in accord with the factor of 4 increase in η_{GP} predicted by G. M. Kennedy & S. J. Kenyon (2008) for stars with $3 M_{\odot} \lesssim M_* \lesssim 4 M_{\odot}$ relative to solar-mass dwarfs.

constrain is approximately equal to the occurrence of giant planets orbiting stars with $M_{*,i} \gtrsim 3 M_{\odot}$ with $a \gtrsim 5$ au.

Theoretical predictions for the occurrence of giant planets orbiting massive stars sensitively depend on the assumptions made in models of planet formation for the relationship between host star mass, disk mass, and disk lifetime (e.g., Y. Alibert et al. 2011). G. M. Kennedy & S. J. Kenyon (2008) predicted that giant planet occurrence should increase by about a factor of 4 from the occurrence observed for solar-mass dwarf stars to stars with $3 M_{\odot} \lesssim M_* \lesssim 4 M_{\odot}$. In contrast, studies of evolved stars with masses in the range $2 M_{\odot} \lesssim M_* \lesssim 3 M_{\odot}$ seem to suggest that the occurrence of Doppler-detectable giant planets orbiting evolved massive stars peaks at $\eta_{\text{GP}} \approx 0.10$ for $M_* \approx 1.8 M_{\odot}$ and drops down to $\eta_{\text{GP}} \approx 0.02$ for $M_* \approx 3 M_{\odot}$, albeit with large uncertainties (e.g., V. Wothoff et al. 2022).

We find $\eta_{\text{GP}} = 0.11^{+0.13}_{-0.07}$ in the mass range $3 M_{\text{Jup}} \lesssim M_p \lesssim 10 M_{\text{Jup}}$ for stars with $M_{*,i} \gtrsim 3 M_{\odot}$. B. J. Fulton et al. (2021) report $\eta_{\text{GP}} \approx 0.02 \pm 0.005$ in the mass range $3 M_{\text{Jup}} \lesssim M_p \lesssim 10 M_{\text{Jup}}$ for solar-mass dwarf stars. In accord

with the G. M. Kennedy & S. J. Kenyon (2008) prediction, as we plot in Figure 6, our η_{GP} inference for massive giant planets orbiting stars with $M_{*,i} \gtrsim 3 M_{\odot}$ is consistent with a factor of 4 increase in the B. J. Fulton et al. (2021) value. At the same time, our η_{GP} inference is also consistent with the value reported by V. Wothoff et al. (2022). Future JWST NIRCам observations of approximately 250 additional white dwarfs from our sample of 2195 Gaia-identified massive, young white dwarfs would provide the statistical precision necessary to evaluate whether or not giant planet occurrence takes on its maximum value in the range $3 M_{\odot} \lesssim M_* \lesssim 4 M_{\odot}$.

5. Conclusion

We used Spitzer/IRAC SEIP Source List photometry to search for unresolved mid-infrared color excesses indicative of unresolved giant planet-mass objects orbiting 51 massive, young white dwarfs with Spitzer/IRAC [3.6] and [4.5] data selected from a larger sample of 2195 massive, young solar-neighborhood white dwarfs. We identify one candidate in the GALEX J071816.4+373139 system with $M_p \approx 3.6 M_{\text{Jup}}$,

$T_{\text{eff}} \approx 400$ K, and $\log g \approx 3.8$. We also use these data to infer the occurrence of giant planets $\eta_{\text{GP}} = 0.11^{+0.13}_{-0.07}$ in the mass range $3 M_{\text{Jup}} \lesssim M_{\text{p}} \lesssim 10 M_{\text{Jup}}$ for stars with initial masses $M_{*,i} \gtrsim 3 M_{\odot}$. This η_{GP} inference is consistent both with the predicted factor of 4 increase in η_{GP} for stars with $3 M_{\odot} \lesssim M_{*} \lesssim 4 M_{\odot}$ relative to solar-mass dwarfs and with Doppler-based η_{GP} inferences for evolved massive stars.

While we argue that the Galactic kinematics of GALEX J071816.4+373139 support our inference that it is a product of the stellar evolution of a single B star and not the merger of two lower-mass white dwarfs, we cannot conclusively eliminate the merger scenario from consideration. If GALEX J071816.4+373139 is the result of the merger of two lower-mass white dwarfs, then our analyses would suggest an upper limit on the occurrence $\eta_{\text{GP}} < 0.025$ for objects with $3 M_{\text{Jup}} \lesssim M_{\text{p}} \lesssim 10 M_{\text{Jup}}$ orbiting main-sequence B stars. Future JWST/NIRCam observations of additional massive, young white dwarfs from our sample will be sensitive to Saturn-mass planets and would provide the definitive measurement of η_{GP} for stars with $M_{*,i} \gtrsim 3 M_{\odot}$.

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under a contract with NASA. This publication makes use of data products from the Wide-field Infrared Survey Explorer, which is a joint project of the University of California, Los Angeles, and the Jet Propulsion Laboratory/California Institute of Technology, funded by the National Aeronautics and Space Administration. This research has made use of the NASA Exoplanet Archive, which is operated by the California Institute of Technology, under contract with the National Aeronautics and Space Administration under the Exoplanet Exploration Program. This research has made use of NASA's Astrophysics Data System.

Facilities: ADS, ESO:VISTA, Exoplanet Archive, Gaia, IRSA, NEOWISE, Spitzer, UKIRT, WISE.

Software: *astropy* (Astropy Collaboration et al. 2013, 2018, 2022), *numpy* (C. R. Harris et al. 2020), *matplotlib* (J. D. Hunter 2007), *R* (R Core Team 2024), *SciPy* (P. Virtanen et al. 2020).




Appendix

In Table 4 below we provide a complete list of the 51 white dwarfs selected from our input sample of 2195 white dwarfs with Spitzer/IRAC SEIP Source List [3.6] and [4.5] photometry. We also include for each white dwarf our inferred T_{eff} , $\log g$, mass, age, color excess, flux excess, and mass range in which a companion would be detectable. We calculate these detectability bounds using the total age of each white dwarf and the uncertainty of its SEIP photometry. We consider a companion detectable when it would produce a color excess in the system 3 times the SEIP color uncertainty for the system. As companion mass increases through the giant planet/brown dwarf regime, flux excesses in both [3.6] and [4.5] increase. The color excess between those two bands is expected to first increase and then decrease, though, as a very massive companion would have a hot temperature and leave the color index close to the Rayleigh–Jeans value. Consequently, our color excess approach is insensitive to both low-mass and high-mass companions.

Table 4
51 Massive, Young White Dwarfs with Spitzer/IRAC SEIP Photometry

| Gaia EDR3 source_id | Distance (pc) | Envelope Type | T_{eff} (K) | $\log g$ | WD Mass (M_{\odot}) | Age (Gyr) | Σ | $\chi_{3.6}$ | $\chi_{4.5}$ | Sensitivity Range | |
|---------------------|------------------|---------------|-------------------------|----------|----------------------------|--------------|----------|--------------|--------------|----------------------|----------------------|
| | | | | | | | | | | (M_{Jup}) | (M_{Jup}) |
| 384841336150015360 | 127.1 | H | 43260 | 8.98 | 1.204 | 0.073 | 2.085 | -1.09 | 1.30 | 3.59 | 11.6 |
| 292454841560140032 | 79.8 | H | 42561 | 9.07 | 1.243 | 0.094 | -0.74 | -0.36 | -0.94 | 2.60 | 11.6 |
| 95297185335797120 | 47.4 | H | 11666 | 8.26 | 0.770 | 1.049 | 22.44 | 52.68 | 120.6 | 4.67 | 41.3 |
| 94150944463779968 | 109.6 | H | 13269 | 8.25 | 0.767 | 0.869 | 1.52 | -1.36 | 0.53 | 14.5 | 41.6 |
| 5170668766392712448 | 70.3 | H | 32945 | 8.57 | 0.994 | 0.146 | -0.34 | -0.24 | -0.54 | 3.04 | 13.6 |
| 4613612951211823104 | 29.5 | He | 31805 | 9.25 | 1.327 | 0.388 | -0.18 | 0.29 | 0.17 | 1.59 | 13.4 |
| 4613612951211823616 | 29.5 | H | 16901 | 8.39 | 0.859 | 0.554 | -0.85 | -0.48 | -1.23 | 3.85 | 33.4 |
| 5060502958330979840 | 134.4 | He | 15609 | 8.31 | 0.786 | 0.707 | 0.38 | 0.51 | 0.71 | 10.5 | 36.8 |
| 216683956238279168 | 40.2 | He | 30047 | 8.63 | 1.027 | 0.168 | -1.52 | 0.78 | -0.74 | 6.58 | 40.1 |
| 3251244858154433536 | 31.2 | H | 45443 | 9.17 | 1.289 | 0.100 | -0.31 | 1.42 | 1.35 | 1.05 | 11.2 |
| 66697547870378368 | 130.1 | He | 35575 | 8.64 | 1.039 | 0.119 | 0.51 | -1.10 | -0.38 | 4.17 | 19.9 |
| 3302846072717868416 | 34.9 | H | 15018 | 8.31 | 0.806 | 0.694 | 0.03 | -0.37 | -0.43 | 4.37 | 37.9 |
| 45980377978968064 | 50.1 | H | 16673 | 8.39 | 0.861 | 0.564 | 0.22 | -0.89 | -0.85 | 4.36 | 34.7 |
| 3313606340183243136 | 44.9 | He | 24007 | 8.35 | 0.820 | 0.409 | -0.59 | 1.05 | 0.81 | 5.15 | 40.6 |
| 3313714023603261568 | 47.8 | H | 25626 | 8.17 | 0.739 | 0.536 | 0.00 | -0.39 | -0.46 | 6.51 | 45.0 |
| 147985404582267648 | 86.7 | H | 36564 | 8.63 | 1.035 | 0.114 | -0.78 | -1.02 | -1.52 | 9.57 | 32.5 |
| 3308403897837092992 | 46.0 | He | 16656 | 8.29 | 0.774 | 0.666 | -1.17 | -0.60 | -1.60 | 5.04 | 40.6 |
| 3201709827802584576 | 171.2 | H | 61895 | 8.82 | 1.143 | 0.053 | 1.46 | 0.26 | 1.71 | 11.3 | 11.8 |
| 3014049448078210304 | 83.5 | H | 36264 | 8.84 | 1.136 | 0.105 | 0.55 | -0.80 | -0.05 | 2.87 | 14.5 |
| 3216947242193857024 | 93.0 | H | 33628 | 8.75 | 1.092 | 0.123 | -0.37 | 0.27 | -0.08 | 2.44 | 16.2 |
| 4656950408184656128 | 81.5 | He | 16625 | 8.74 | 1.060 | 0.691 | 0.32 | 16.36 | 11.94 | 6.63 | 31.3 |
| 2884285498084601600 | 195.2 | H | 11092 | 7.80 | 0.743 | 0.494 | 0.18 | -0.55 | -0.54 | >80 | >80 |
| 898348313253395968 | 85.3 | He | 37889 | 9.33 | 1.372 | 0.622 | 4.26 | -1.08 | 3.12 | 2.45 | 11.7 |
| 976040702520790400 | 32.4 | H | 14409 | 8.61 | 0.994 | 0.736 | -0.37 | -0.12 | -0.44 | 3.47 | 32.6 |
| 604972428842238080 | 77.6 | H | 11246 | 8.47 | 0.903 | 1.161 | 1.68 | -1.98 | -0.35 | 6.57 | 40.2 |
| 1044784918268692224 | 73.0 | H | 19579 | 8.16 | 0.720 | 0.675 | 1.51 | -0.83 | 0.17 | 6.43 | 44.2 |
| 5461296765091298048 | 90.9 | H | 35304 | 8.97 | 1.192 | 0.134 | 0.92 | -0.43 | 0.66 | 3.23 | 13.2 |
| 834234385783616640 | 78.7 | H | 20275 | 8.14 | 0.707 | 0.720 | -2.41 | 1.58 | -0.19 | 6.12 | 41.8 |
| 1055273537642488576 | 62.6 | H | 24223 | 8.46 | 0.912 | 0.287 | 0.58 | -0.22 | 0.20 | 2.92 | 24.6 |
| 730459763934332416 | 37.8 | H | 22763 | 8.39 | 0.870 | 0.372 | 0.98 | -1.20 | -0.69 | 3.81 | 31.2 |
| 3564376149017654272 | 46.8 | H | 24638 | 8.69 | 1.052 | 0.240 | 0.49 | -1.15 | -0.69 | 2.68 | 20.9 |
| 789339608048607232 | 48.2 | H | 12514 | 8.26 | 0.769 | 0.942 | 0.77 | -0.93 | -0.48 | 5.29 | 41.3 |
| 783880704600816000 | 85.1 | He | 34725 | 8.49 | 0.948 | 0.164 | -1.36 | 0.70 | -0.78 | 5.14 | 25.1 |
| 3698872156539379968 | 59.0 | H | 19670 | 8.30 | 0.811 | 0.497 | 0.69 | -0.79 | -0.39 | 4.34 | 33.9 |
| 1582231699483080192 | 199.4 | H | 12785 | 7.51 | 0.730 | ... | -1.35 | -1.15 | -2.25 | ... | ... |
| 1572889389701360384 | 105.7 | H | 59018 | 7.99 | 0.708 | 0.629 | 0.55 | 0.32 | 0.80 | 16.0 | 70.4 |
| 1579147088331814144 | 59.3 | He | 28947 | 8.22 | 0.746 | 0.504 | 0.48 | 1.16 | 1.79 | 4.98 | 37.1 |
| 1551062778220116992 | 32.9 | H | 14610 | 8.37 | 0.844 | 0.699 | 0.31 | -0.64 | -0.52 | 4.13 | 34.8 |
| 1685171001732519808 | 85.3 | He | 36060 | 8.40 | 0.899 | 0.216 | -1.22 | -0.75 | -1.71 | 4.30 | 30.5 |
| 1479511096971183872 | 105.1 | H | 14150 | 8.19 | 0.731 | 0.862 | -1.05 | 0.85 | -0.25 | 7.43 | 41.7 |
| 1281410781322153216 | 48.3 | H | 22637 | 8.37 | 0.855 | 0.387 | -0.28 | 0.33 | 0.16 | 3.48 | 30.2 |
| 5779908502946006784 | 124. | H | 47344 | 9.08 | 1.246 | 0.066 | -1.04 | 3.84 | 1.53 | 2.03 | 11.4 |
| 6009760034351291904 | 89.8 | H | 51678 | 8.95 | 1.195 | 0.045 | -0.31 | 1.41 | 1.08 | 1.64 | 11.6 |
| 1202826348825240832 | 36.8 | H | 14788 | 8.40 | 0.868 | 0.681 | -0.21 | -0.51 | -0.75 | 4.33 | 34.7 |
| 1629292579563565696 | 137.5 | He | 38312 | 8.73 | 1.084 | 0.093 | -0.99 | -0.24 | -1.11 | 3.19 | 13.0 |
| 1356434445415005184 | 134.3 | H | 28175 | 8.28 | 0.811 | 0.373 | -0.84 | 0.03 | -0.73 | 6.65 | 33.4 |
| 1358301480583401728 | 31.5 | H | 30054 | 9.25 | 1.324 | 0.453 | -0.24 | -0.55 | -0.80 | 1.80 | 14.8 |
| 1634314740658456320 | 173.2 | H | 89534 | 7.90 | 0.732 | 0.527 | -0.47 | 0.43 | 0.18 | 27.9 | 79.3 |
| 5810075116283522688 | 130.1 | H | 46769 | 8.87 | 1.157 | 0.056 | -1.01 | 0.66 | -0.55 | 2.65 | 11.9 |
| 4078868662206175744 | 50.4 | He | 39161 | 8.28 | 0.830 | 0.321 | -0.18 | 2.12 | 2.31 | 4.63 | 33.6 |
| 2262849634963004416 | 12.8 | He | 12086 | 8.58 | 0.957 | 1.154 | 0.94 | 0.40 | 1.20 | 3.87 | 36.2 |
| 2286107295188538240 | 71.3 | He | 13935 | 8.19 | 0.709 | 0.978 | 1.88 | 2.59 | 4.71 | 5.93 | 44.1 |

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