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Gamma Cas Stars as Be+White Dwarf Binary Systems

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Abstract

The origin of the bright and hard X-ray emission flux among the γ Cas subgroup of B-emission line (Be) stars may be caused by gas accretion onto an orbiting white dwarf (WD) companion. Such Be+WD binaries are the predicted outcome of a second stage of mass transfer from a helium star mass donor to a rapidly rotating mass gainer star. The stripped donor stars become small and hot white dwarfs that are extremely faint compared to their Be star companions. Here we discuss model predictions about the physical and orbital properties of Be+WD binaries, and we show that current observational results on γ Cas systems are consistent with the expected large binary frequency, companion faintness and small mass, and relatively high mass range of the Be star hosts. We determine that the companions are probably not stripped helium stars (hot subdwarf sdO stars), because these are bright enough to detect in ultraviolet spectroscopy, yet their spectroscopic signatures are not observed in studies of γ Cas binaries. Interferometry of relatively nearby systems provides the means to detect very faint companions including hot subdwarf and cooler main-sequence stars. Preliminary observations of five γ Cas binaries with the CHARA Array interferometer show no evidence of the companion flux, leaving white dwarfs as the only viable candidates for the companions.

Unified Astronomy Thesaurus concepts: Spectroscopic binary stars (1557); Emission line stars (460); Stellar evolution (1599)

1. Introduction

B-emission line (Be) stars are rapidly rotating B-type stars that are losing gas and angular momentum into a circumstellar decretion disk (Rivinius et al. 2013). Some of these stars were spun up through a prior stage of mass transfer in an interacting binary (Pols et al. 1991; Hastings 2021; Shao & Li 2021), and the former donor star appears as a stripped-down remnant (He star, neutron star, or white dwarf). Although faint, the remnants are detected as Be+sdO (hot subdwarf) systems through ultraviolet spectroscopy (Wang et al. 2021) and as Be+NS systems as Be X-ray binaries (BeXRBs; Reig 2011). Most Be stars are modest X-ray sources with luminosities comparable to normal B-type stars (Nazé et al. 2022b), but in addition to the BeXRBs, there is a subset of Be stars that have an unusually large and hard X-ray flux. This group is known as the γ Cas stars or analogs, named after the bright prototype of the group (Smith et al. 2016). There are several explanations for their bright X-ray flux. The first envisions the creation of strong and localized magnetic fields near the star–disk interface that can generate high-temperature gas through flares (Smith et al. 1998; Smith & Robinson 1999). The second idea is that X-ray flux is generated by accretion onto a compact white dwarf (WD) as occurs in cataclysmic variables (Murakami et al. 1986; Hamaguchi et al. 2016). Models of the X-ray spectrum for accretion onto a magnetic or nonmagnetic WD provide good fits of the X-ray spectra of γ Cas and HD 110432 (Tsujimoto et al. 2018) and π Aqr (Tsujimoto et al. 2022). Postnov et al. (2017) suggest a third scenario in which the companion is a rapidly spinning neutron star that avoids gas accretion through a "propeller" mechanism, but Smith et al. (2017) argue that this idea fails to account for the number and observational properties of the γ Cas group.

The binary origin is partially motivated by the fact that several of the brightest γ Cas stars are known binaries, including γ Cas itself (Nemravova et al. 2012) and π Aqr (Bjorkman et al. 2002). Recently Nazé et al. (2022a) presented the results of a radial velocity survey of 16 γ Cas stars that suggest that many are binaries. They found orbits for six previously unknown binaries and identified five other probable binaries that display significant velocity variability. These are all long-period binaries with low-mass companions whose flux was not detected. These properties are expected for WD companions, but Nazé et al. (2022a) caution that these may also be systems with sdO companions that generally are not X-ray bright (Nazé et al. 2022b). If so, then a binary companion alone is not a sufficient explanation for the X-ray properties of the γ Cas stars, and the magnetic origin remains as an attractive explanation.

Here we present several arguments that any sdO companions of the γ Cas stars should be bright enough to detect through ultraviolet spectroscopy and near-IR interferometry. We suggest that the lack of any such detections to date indicates that the companions must be much fainter as expected for WD stars. These considerations suggest that the γ Cas stars probably have WD companions and that accretion onto the WD remains as a viable theory for their bright X-ray flux.

2. Formation Models

The Be+sdO binaries were probably formed through Case B mass transfer in which the donor filled its Roche surface during the expansion that occurred with the initiation of H-shell burning (Pols et al. 1991; Shao & Li 2021). Most of the sdO

Table 1
Sample Be+WD System Parameters

Parameter	High Mass			Low Mass		
	Be	WD	MS	Be	WD	MS
M ($\mathcal{M}_\odot^{\rm N}$)	11.1	1.2	1.2	6.5	0.7	0.7
R ($\mathcal{R}_\odot^{\rm N}$)	5.4	0.006	1.3	3.9	0.012	0.7
$T_{\rm eff}$ (kK)	25	57	6.2	19	42	4.4
$\triangle m$ (1450 Å) (mag)	0	12.7	24.4	0	9.8	36.6
$\triangle m$ (1.65 μm) (mag)	0	13.7	4.8	0	11.5	5.5

stars represent the stripped-down remnants after completion of mass transfer, and they maintain their luminosity through He-core burning (Götberg et al. 2018). After a time comparable to or less than the main-sequence (MS) lifetime of the nearby Be star, the sdO stars will initiate He-shell burning and again grow in radius and luminosity (Schootemeijer et al. 2018; Laplace et al. 2020).

This next stage of enlargement will lead to a second Roche-filling and mass transfer episode that is sometimes called Case BB (Delgado & Thomas 1981). In general, if the remnant after this second mass transfer stage has a core mass greater than 1.4 $\mathcal{M}_\odot^{\rm N}$,[5] then the star will quickly experience advanced nuclear burning and explode as a H-poor supernova. In the lower-mass case, nuclear burning will cease and the remnant will rapidly enter the WD cooling sequence as a CO WD (or ONe WD for larger masses; Dewi et al. 2002).

Detailed examples of this second mass transfer stage are given in studies by Habets (1986, see his Figure 8) and by Willems & Kolb (2004, see their Figure 4 and Section 3.1.2). Both of these models indicate that the sdO star loses about 12% of its mass through mass transfer to the Be star, and the post-mass-transfer binary has a lower mass ratio M_2'/M_1' and a slightly longer orbital period. Willems & Kolb (2004) present population statistics from their models of this evolutionary stage (that they call "Channel 2"). They find that the WD remnants have masses in the range 0.7–1.4 $\mathcal{M}_\odot^{\rm N}$ and orbital periods in the range 40–1000 days (peaking at 200 days; see their Figure 2, middle right panel). The mass gainer (Be) stars end up with masses spanning the range of 7–17 $\mathcal{M}_\odot^{\rm N}$ (see their Figure 3, middle right panel).

The remnants with core mass below the Chandrasekhar limit will begin their lives as hot and small WDs shortly after the second mass transfer episode when nuclear burning ends. Bédard et al. (2020) show examples of cooling curves for CO WDs for different ages and remaining H coverage (see their Figure 6). We list in Table 1 two examples of the probable stellar properties for remnant WD masses of 1.2 and 0.7 $\mathcal{M}_\odot^{\rm N}$. The WD radii and temperatures are adopted from Bédard et al. (2020) for their H-thick envelope case and an age of 3.2 Myr (comparable to the ages of the more massive Be star companions). We estimate the corresponding Be star masses by assuming conservative mass transfer so that the post-mass-transfer mass ratio is

$$\frac{M_1'}{M_2'} = \frac{M_1 + \triangle M_2}{M_2 - \triangle M_2} = \frac{\frac{M_1}{M_2} + \frac{\triangle M_2}{M_2}}{1 - \frac{\triangle M_2}{M_2}}.$$

The mass ratio in the Be+sdO stage is approximately $M_1/M_2 = 8.0$ from the recent compilation by Wang et al. (2023), and we assume a mass-loss fraction in the second stage from the models cited above of $\triangle M_2/M_2 = 12\%$. The post-mass-transfer mass ratio is then approximately $M_1'/M_2' = 9.2$, and we use this ratio to determine the mass of the Be star quoted in Table 1. We set the Be star temperature and radius from the MS mass calibration given by Pecaut & Mamajek (2013). We also show in Table 1 the parameters from Pecaut & Mamajek (2013) for low-mass MS stars of the same mass as assumed for the WDs.

In order to illustrate just how faint the WD companions are at the start of the WD cooling sequence, we created model spectral energy distributions for each case using model fluxes from TLUSTY for the WD (OSTAR2002; Lanz & Hubeny 2003) and the Be star (BSTAR2006; Lanz & Hubeny 2007) and from ATLAS9 (Castelli & Kurucz 2003) for the low-mass MS case. The stellar flux ratio f_2/f_1 was calculated as a function of wavelength by multiplying the model flux ratio by the square of the radius ratio. Table 1 gives the resulting flux ratios expressed as a magnitude difference for the cases of the far-ultraviolet spectrum (evaluated at 1450 Å) and of the near-infrared H band (1.65 μm). We find that a WD companion would be too faint to detect by current means in both bands ($\triangle m > 10$ mag), while an MS companion might be found in the near-infrared.

We caution that the estimates in Table 1 do not account for the possible added flux from disks around both components. Be star disks produce a continuum excess that grows with wavelength and may change the flux from the Be star and its decretion disk by as much as 0.3 mag in the H band (Touhami et al. 2010). This would increase the magnitude difference between the Be star and its companion by the same amount. On the other hand, flux from accreting gas surrounding the WD could increase the WD apparent brightness and cause a decrease in the magnitude difference. For example, there is a hot continuum flux component in the far-ultraviolet (FUV) spectra of some dwarf novae in quiescence that can make the system appear about 0.5 mag brighter than expected for the WD alone (Long et al. 2005; Urban & Sion 2006). However, adjustments of this size for the magnitude difference will not change the basic conclusion from Table 1 that the WDs are too faint to detect.

3. Observational Tests

There are a number of tests and predictions that follow from the Be+WD scenario for the γ Cas stars that are particularly valuable given recent spectroscopic and interferometric investigations of Be stars in the group. Here we outline these tests and compare the expectations with observational results. The main predictions are given at the beginning of each subsection.

3.1. Binary Frequency

All γ Cas stars are predicted to be long-period binaries with low-mass companions. It is difficult to evaluate the binary status of Be stars in general and the γ Cas stars in particular because the Doppler shifts of the Be stars are small compared to their rotationally broadened line widths and because the orbital periods are long. Thus, spectroscopic investigations are demanding and require high-quality observations obtained over long time spans. In addition, it is important to account for selection effects

[5] Nominal IAU solar units; Prsa et al. (2016).

introduced by random orbital inclination. Nevertheless, the seminal radial velocity study by Nazé et al. (2022a) does indicate that a large fraction of the γ Cas stars are binaries with low-mass companions. Of the 26 γ Cas stars known at this time (Nazé et al. 2020; Nazé et al. 2022b), 10 are binaries with established orbits and 5 are candidate binaries (Nazé et al. 2022a). The remaining stars generally have too few radial velocity measurements to determine the binary status. It is reasonable to conclude that most γ Cas stars are binaries, but more work will be needed to determine if all members are binaries.

3.2. Magnitude Difference

The WD companions are very faint compared to the Be components. We showed sample cases of the expected magnitude differences in Table 1, and these show that the WD flux is probably not detectable by current observational methods. On the other hand, a number of recent investigations demonstrate that the flux of brighter sdO companions can be directly observed across the spectrum, so it should be possible to determine if the companions are helium stars (sdO/sdB) or WDs.

Recent studies by Wang et al. (2021, 2023) summarize the advances in FUV spectroscopy that have led to the detection of the spectral signature of the hot sdO components in some 20 cases to date with a magnitude difference around $\triangle m$(1450 Å) ~3.5 mag. Most of these sdO stars are in the relatively fainter stage of He-core burning (see Wang et al. 2021, Figure 17), and this suggests that FUV spectroscopy should be able detect most of the sdO companions in Be+sdO binaries. Figure 1 illustrates the expected magnitude difference from the models of Götberg et al. (2018) for the sdO star and from the associated MS star parameters (Pecaut & Mamajek 2013) for the Be star with masses estimated from $M_1/M_2 = 8.0$ (Wang et al. 2023). The plotted magnitude difference as a function of sdO mass confirms that the predicted and observed sdO fluxes are above the detection limit for Hubble Space Telescope (HST) FUV spectroscopy, $\triangle m$(1450 Å) < 4.4 mag (Wang et al. 2021).

However, in contrast to the Be+sdO systems, all the FUV investigations to date of γ Cas stars have led to null detections. These include studies of International Ultraviolet Explorer (IUE) spectra of γ Cas, π Aqr, and ζ Tau (Wang et al. 2017); HD 45995 and HD 183362 (Wang et al. 2018); and HST spectra of HD 157832 (Wang et al. 2021). It is striking that no sdO component was found for these six binaries, but it is consistent with the idea that the companions of γ Cas stars are faint WDs. Based upon their expected faintness (Table 1), we predict that future HST FUV spectroscopy will yield no detections of companions for the γ Cas stars.

The FUV results are confirmed in a recent visible-band spectroscopic investigation by Wang et al. (2023), who detected the presence of the He II λ4686 absorption line in the spectrum of the sdO star in four cases but found it was absent in the case of the γ Cas star HD 157832. This again indicates that the companion star in HD 157832 is fainter than expected for an sdO star, and the lack of detection is consistent with a WD companion.

Optical long baseline interferometry offers another means to investigate the companion flux of Be binaries that are close enough for their components to be angularly resolved. For example, sensitive closure phase measurements with the CHARA Array enable detection of companions with magnitude differences as large as $\triangle m(1.65\ \mu\mathrm{m}) = 6.4$ (Gallenne et al. 2015; Roettenbacher et al. 2015). CHARA Array observations have already successfully detected the companions and mapped the orbits of three Be+sdO and one Be+sdB binary systems (Klement et al. 2022a, 2022b), and a survey of other targets is underway. If the companions in γ Cas binaries are low-mass MS stars, then these interferometric observations will detect them because they are relatively bright in the *H* band (Table 1). Furthermore, any sdO companions will also be bright enough for detection in the *H* band (Figure 1). If, on the other hand, no companion flux is found, then the only remaining possibility is that the companions are faint WDs. Preliminary analysis of CHARA Array observations of five γ Cas targets indicates no evidence of the flux of a companion (R. Klement et al., in preparation), which would rule out any sdO (Figure 1) or MS (Table 1) companion.

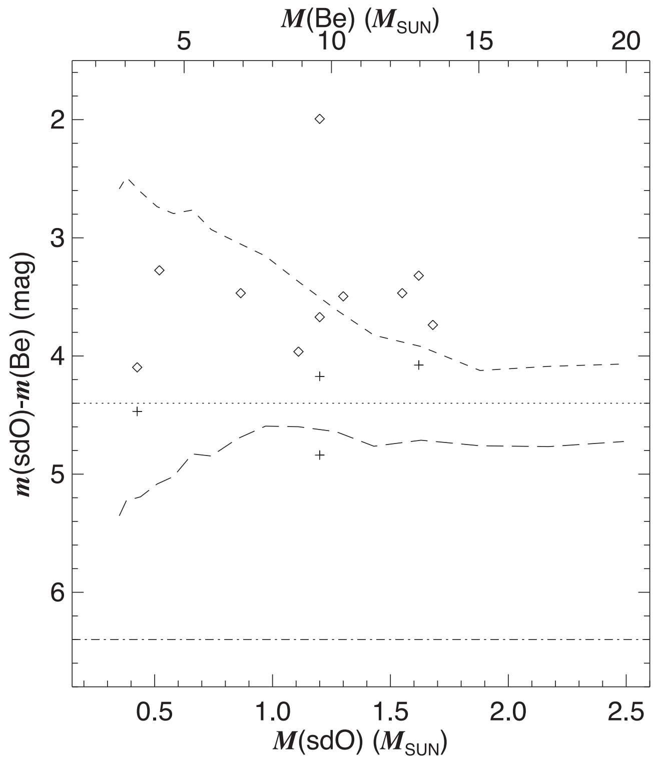

Figure 1. Predicted magnitude differences for Be+sdO binaries based upon the sdO flux models from Götberg et al. (2018) for stars at the halfway point of He-core burning. The Be stars are assumed to have masses 8× larger than the sdO stars and have temperatures and radii associated with main-sequence values for the mass. The upper, short-dashed line shows the predicted magnitude difference at 1450 Å (FUV) while the lower, long-dashed line is for 16500 Å (near-infrared *H* band). Diamonds indicate observed values from FUV studies, and the crosses show those from CHARA Array *H*-band interferometry. The FUV predictions and observations all are brighter than the faint limit of HST spectroscopy (middle dotted line), and the *H*-band models and observations are all much brighter than the detection limits of the CHARA Array (lower dotted–dashed line). These comparisons indicate that current observational methods are sufficient to detect the faint companion stars in most or all Be+sdO systems (but not in the case of Be+WD binaries).

3.3. Mass Ratio

The mass ratios of Be+WD binaries will be somewhat lower than those of Be+sdO systems. The second mass stripping episode will further decrease the remnant mass, and models suggest that the proto-WD will lose about 12% of its mass. It is difficult to determine the mass ratio in the absence of a double-lined spectroscopic orbital solution, but estimates are possible using the single-lined mass function plus estimates for the Be star mass and the orbital inclination. The estimated mass ratios for the well-studied γ Cas stars are $q = M_2/M_1 = 0.075$ for γ Cas (Nemravova et al. 2012), 0.086 for ζ Tau (Ruzdjak et al. 2009), 0.067 for HD 157832 (Wang et al. 2023), and 0.08 for π Aqr (Tsujimoto et al. 2022). These are all lower than the average value for Be+sdO systems of $q = 0.125 \pm 0.037$ (Wang et al. 2023) as expected if the companions of the γ Cas stars are lower-mass WDs.

Furthermore, the estimated companion masses are generally $<1\mathcal{M}_\odot^{\rm N}$, which is too low for a neutron star (Fortin et al. 2016). The one exception is the binary π Aqr, which Bjorkman et al. (2002) estimate has a companion of mass $2\mathcal{M}_\odot^{\rm N}$. However, Naze et al. (2019) and Tsujimoto et al. (2022) have made new measurements of the Be star orbital velocity, and they both derive a semiamplitude that is 2× smaller than that found by Bjorkman et al. (2002). This decrease leads to a smaller estimate of companion mass, $<1\mathcal{M}_\odot^{\rm N}$, so the companion in the π Aqr system does have a mass appropriate for a WD. Bjorkman et al. (2002) found a weak Hα emission component that displayed an antiphase radial velocity variation, and they suggested that the emission originates in the vicinity of the companion. This feature was conspicuous in spectra obtained between 1996 and 2000 when the Hα disk emission was otherwise weak and confined to the extreme line wings, but subsequent spectra obtained when the disk was dense and large do not show this moving component (Naze et al. 2019). The Hα morphology described by Bjorkman et al. (2002) bears a strong resemblance to that seen in the He I λ6678 line of the Be +sdO binary ϕ Per, and the antiphase motion in the latter case is explained as arising in a bright region of the Be star disk that faces and is illuminated by the hot companion (Štefl et al. 2000; Hummel & Stefl 2001). Zharikov et al. (2013) find evidence of a similar bright region in the disk of π Aqr that faces the companion. Thus, we suggest that the emission component described by Bjorkman et al. (2002) probably formed in the part of the Be disk directed toward the companion and not in an accretion zone around the WD. If so, then the mass ratio they derived from the emission velocity curve, $M_2/M_1 = 0.16$, is unreliable and is probably much larger than the actual value ($M_2/M_1 = 0.08 \pm 0.04$; Tsujimoto et al. 2022).

3.4. Be Star Properties

The Be primaries in γ Cas binaries will generally have high masses, very rapid rotation, and He-enriched atmospheres. The second stage of mass transfer will probably add to the already large angular momentum of the mass gainer Be star, and the accreted gas may have a high proportion of nuclear processed He (and possibly C through the triple-α process). The γ Cas stars are generally found only among the more massive, early-type Be stars (Smith et al. 2016; Nazé et al. 2020), which is consistent with the mass range of the gainer stars predicted by Willems & Kolb (2004) of 7–17 $\mathcal{M}_\odot^{\rm N}$. Furthermore, more massive Be stars will probably have more massive WD companions that have smaller radii, and outward leakage from the more massive Be star disks will yield a higher mass accretion rate by the WD. Both factors will result in a higher accretion luminosity from the WD.

4. Conclusions

The strong and hard X-ray emission flux observed in the γ Cas stars may result from gas accretion onto a small WD companion. Indeed, we argued here that the γ Cas binaries represent the progeny of the Be+sdO systems that are created after a second mass transfer stage that leads to the transformation of the helium star into a WD. We discussed the observational consequences of this Be+WD scenario for the γ Cas stars, and we reviewed four broad tests of the validity of the model. The general observed properties are consistent with WD companions: a large fraction of γ Cas stars are known, long-period binaries; the contrast in companion to Be star flux is too small to detect the companion's flux; the estimated mass ratios indicate companion masses below the Chandrasekhar limit; and the Be star hosts are very fast rotators at the high end of the Be star mass range. We demonstrated that the unseen companions in these systems are probably not subdwarf sdO stars, because the sdO stars are large and bright enough to detect their flux through analysis of ultraviolet spectroscopy, yet none have been detected thus far among the γ Cas stars. Near-infrared interferometric observations of targets that are near enough to resolve their orbits offer even more stringent limits on faint companions, and nondetection will rule out both helium star and MS star companions. Preliminary analysis of interferometry from the CHARA Array of five γ Cas systems shows no evidence of the companion flux, and this leaves only WDs as viable companion candidates.

The direct detection of such WD companions remains a daunting task because they are so much fainter than their Be star companions. It is possible that nulling interferometers (Defrère et al. 2022) and coronagraphic imagers with extreme adaptive optics (Davies et al. 2021) may be able to resolve and detect nearby Be+WD systems. Detection might also be possible through spectroscopic reconstruction methods based upon very high signal-to-noise ratio and high resolving power observations that fully cover the orbital cycle. For example, Gies et al. (2020) were able to detect the spectral signal from the WD companion of the B-star Regulus with a magnitude difference of $\triangle m(V) = 8.1$ mag from a large set of high-quality, visible wavelength spectra. However, until such difficult observations are made, the best evidence for the WD companions of the γ Cas stars is the consistent absence of their flux in the available observations because of their extreme faintness.

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Software: TLUSTY (Lanz & Hubeny 2003, 2007), ATLAS9 (Castelli & Kurucz 2003).

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