Gamma Cassiopeiae and HR 266: A Massive Septuplet Illuminating the IC 59 and IC 63 Nebulae at d = 168 pc

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Abstract: The unusual prototype Be shell star γ Cas is part of a triple system (WDS J00567+6043) that illuminates two arc-shaped nebulae: IC 59 and IC 63. The HR 266 system (WDS J00568+6022) is a massive quadruple lying 1274" away from γ Cas (projected separation 1.0 pc), opposite of the reflection nebulae, which appears to be physically associated with this system based on common proper motion, radial velocity, and parallax. The entire γ Cas system appears to constitute a massive septuplet (at least), with approximately 15 $\mathcal{M}_{Sun}$ in mass associated with the γ Cas triplet, and about 13.5 $\mathcal{M}_{Sun}$ in mass associated with the HR 266 quadruplet. The γ Cas system appears to be one of the highest multiplicity systems known (N=7).

Introduction:

γ Cas (HR 264, HIP 4427, ADS 782, 2MASS J00564251+6043002) is a famous eruptive Be shell star, which has shown irregular brightness variations since its discovery as the first Be star by Secchi (1867; see historical discussion by Harmanec, *et al.* 2000 and also Jim Kaler's summary at http://stars.astro.illinois.edu/sow/cas.html).

It is listed with magnitude V = 2.15 in the Hipparcos catalog (ESA 1997), but V = 2.47 in the Bright Star Catalog (Hoffleit & Warren 1991). γ Cas has varied between approximately V ~ 1.6 to 3.0 over much of the past century, and at times it outshines both α Cas (Schedar; V ~ 2.2) and β Cas (Caph; V ~ 2.2), making it the brightest star in the "W" of Cassiopeia. The XHIP catalog (Anderson & Francis 2012) places γ Cas as the 28th most luminous star known within 200 pc of the Sun. γ Cas illuminates two bright rim nebulae in its immediate vicinity (IC 59 and IC 63) as well as a small, irregular H II region nearly 3 deg in diameter (Karr, *et al*. 2005). γ Cas and the nebulae IC 59 and IC 63 are shown in Digitized Sky Survey imagery shown in Figure 1.

γ Cas A is a spectroscopic binary with P = 203 day (Harmanec, *et al*. 2000; Nemravova, *et al*. 2012). The primary Aa is a B0.5IVe with mass ~13 $\mathcal{M}_{Sun}$[1], and the secondary Ab has a mass of approximately 1.0 $\mathcal{M}_{Sun}$ (Nemravova, *et al*. 2012). The primary Aa itself has a 1.1 day photometric periodicity which has been attributed to a close-in white dwarf companion (Apparao 2002), however the existence of such a companion has not yet been confirmed, and more recent work favors this periodicity as being due to the primary's rotation (e.g. Shrader, *et al*. 2015). The circumstellar disk of the Be star has been resolved interferometrically, and the disk appears to have inclination 42° (Stee, *et al*. 2012). With this inclination, γ Cas A is likely rotating near its critical velocity (Stee, *et al*. 2012). The γ Cas A pair companion further out at 2.2" separation (WDS J00567+6043 B = BU 1028) appears to be a V=10.9 F6V star sharing common proper motion. The WDS lists another companion at wider separation (WDS J00567+6043 C) at separation 54.3" with V=12.9, however the UCAC4 proper motion of this star (UCAC4 754-011021 = 2MASS J00564070+6043518; μ_α, μ_δ = -5.3 ± 2.7, +9.3 ± 3.8 mas/yr) is a poor match for γ Cas A (μ_α, μ_δ = +25.17 ± 0.08, -3.92 ± 0.08 mas/yr; van Leeuwen 2007), so it is unlikely to be a physical companion. At present, the γ Cas system appears to be at least a triple with a total mass of ~15 $\mathcal{M}_{Sun}$. Adopting

1. "$\mathcal{M}_{Sun}$" throughout should be understood to be nominal solar mass units, equivalent to the IAU 2015 nominal solar mass parameter ($\mathcal{G}\mathcal{M}_{\odot}$) divided by the CODATA 2014 estimate of the Newtonian gravitational constant $\mathcal{G}$ (Prsa, *et al*. 2016).

Table 1. Positions, Proper Motions, and Trignometric Parallaxes for g Cas and HR 266 from revised Hipparcos Catalog

NAME	RA(deg)	Dec(deg)	pmRA(mas/yr)	pmDec(mas/yr)	plx(mas)
γ Cas	014.17708782	60.71674955	25.17±0.08	-3.92±0.08	5.94±0.12
HR266	014.19558681	60.36284788	26.13±0.30	-3.79±0.33	6.06±0.41

its trigonometric parallax from van Leeuwen (2007) of 5.94 ± 0.12 mas, and its radial velocity from Harmanec, *et al*. (2000) of -7.38 ± 0.64 km/s, I estimate the velocity of the γ Cas system in Galactic coordinates to be U, V, W = -12.7, -17.4, -2.4 (± 0.5, 0.5, 0.4) km/s (total heliocentric velocity 21.6 ± 0.5 km/s).

HR 266 (ADS 784, WDS J00568+6022, 2MASS J00564697+6021463) is a quadruple system consisting of stars of type B7IV (A), B9IV HgMn (Ba), and A1V (Bb) star, plus an astrometrically detected component Bc which may be a single B/A-type star or a pair of lower-mass stars (Fekel 1979, Cole, et al. 1992, Docobo & Andrade 2006). The system lies ~0.35 degree south of γ Cas, diametrically opposite of the IC 59 nebula (Fig. 1). Component B splits into Ba and Bb with a short orbital period of 4.2 days, and that duo orbits the unseen star Bc with period 4.8 yr, detected via speckle astrometry as a perturbation on the motion of Ba+Bb around A (see e.g. Fig. 7 of Cole, et al. 1992). The B trio and component A have a well-characterized visual orbit with period 83 yr. The component C listed in the WDS at separation 41.3" (BU 1353; PA = 157 deg) has near-IR colors consistent with a K3 dwarf. However the star is approximately a magnitude too faint to be a dwarf co-distant with HR 266, and so it is a likely interloper.

The HR 266 system has at least 4 components, and possibly 5 if Bc is a tight pair as speculated by Cole, et al. (1992). The total mass of the HR 266 system is approximately 13.5 $\mathcal{M}_{Sun}$ (Cole, et al. 1992). Adopting the revised Hipparcos parallax for the system (6.06 ± 0.41 mas; van Leeuwen 2007) and the radial velocity from Cole, et al. (1992) of -8.7 ± 0.2 km/s, I estimate the velocity of the HR 266 system in Galactic coordinates to be U, V, W = -12.2, -18.7, -2.2 (±1.2, 0.7, 0.4) km/s (total velocity 22.4 ± 0.9 km/s).

The positions, proper motions, and trigonometric parallaxes for γ Cas and HR 266 in the revised Hipparcos catalog (van Leeuwen 2007; epoch 1991.25, ICRS) are given in Table 1.

Using the revised Hipparcos astrometry, HR 266 lies at separation 1274.4669 ± 0.0004 arcseconds from γ Cas at position angle 178.52 deg. The uncertainty in the separation is dominated by the uncertainty in the position of HR 266 (± 0.3, 0.4 mas in RA, Dec), as the uncertainty in the position of γ Cas is 0.07 mas in both RA and Dec. The revised Hipparcos trigonometric parallaxes for γ Cas (5.94 ± 0.12 mas) and HR 266 (6.06 ± 0.41 mas) from van Leeuwen (2007) are statistically consistent (differing only at the 0.3σ level), and correspond to distances of 168.4 ± 3.4 pc and 165.0 ± 11.2 pc, respectively. Their weighted mean trigonometric parallax (5.95 ± 0.12 mas) is consistent with a distance of 168.1 ± 3.3 pc. At this distance, the projected separation is 214,000 AU or 1.04 pc. The tidal radii t_d for the individual subsystems γ Cas and HR 266 can be estimated using the expression in Mamajek, *et al*. (2013): $r_t = 1.35$ pc $(M_{tot}/\mathcal{M}_{Sun})^{1/3}$. Using the previously mentioned subsystem mass estimates, I estimate the tidal radii of the γ Cas and HR 266 subsystems to be $t_d \sim 3.3$ and 3.2 pc, respectively. The stars are clearly projected within ~1 pc of each other, and their trigonometric parallax distances are statistically consistent to within ~3 ± 12 pc. Their proper motions differ negligibly – Δ(pmRA) = 0.96 ± 0.31 mas/yr and Δ(pmDec) = 0.13 ± 0.34 mas/yr. At d = 168 pc, these differences in proper motion translate to a miniscule difference in tangential velocity of 0.77 ± 0.37 km/s. The radial velocities for γ Cas and HR 266 (from Harmanec, *et al*. 2000, Cole, *et al*. 1992, respectively) differ only at the 1.3 ± 0.7 km/s. Indeed, when comparing the 3D velocity vectors previously calculated, we see that they only differ at the Δ(U,V,W) = -0.5, 1.3, -0.3 (± 1.3, 0.8, 0.5) km/s level. Hence, γ Cas and HR 266 are not only very close in position and distance, but they are demonstrably co-moving to within 1.4 ± 1.6 km/s. This case is fairly similar to the examples of the very wide Mizar-Alcor sextuplet (Mamajek, *et al*. 2010) and the case of Fomalhaut B and C (Mamajek, *et al*. 2013). I conclude that the γ Cas+HR 266 system is likely to be physical, designate it MAM 20, and list HR 266 as component "D" to WDS 00567+6043 (B. Mason, priv. comm.). Table 2 gives PA, separation and magnitudes of the proposed MAM 20 multiple system.

Discussion

Eggelton & Tokovinin (2008) examined the multiplicity of the 4559 brightest stars (V < 6) and identified only 2 septuplets (ν Sco and AR Cas), and none of higher multiplicity. Both of these systems appear to be quite young (< tens Myr) and within OB associations (Sco-Cen and Cas-Tau, respectively). A search for ad-

Table 2. Measurements of MAM 20

NAME	RA+DEC	MAGS	PA	SEP	DATE	N	NOTE
MAM 20	00567+6043	2.15, 5.56	178.5	1274.5	1991.25	1	1

1. Revised Hipparcos astrometry (van Leeuwen 2007), magnitudes from original Hipparcos catalog (ESA 1997).

ditional co-moving stars in the close vicinity (<1°) of γ Cas system has yielded no interesting candidates, however the system could be a cluster remnant of a subgroup within the greater Cas-Tau OB association (see Fig. 19 of de Zeeuw, *et al*. 1999). The Cas-Tau OB association is an extremely diffuse stellar group, and despite its proximity (d ~ 170 pc) it has been barely studied since it was first proposed by Blaauw (1956). Age estimates range from 20 to 50 Myr (e.g. Blaauw 1956, Blaauw 1983, de Zeeuw & Brand 1985), however it has been proposed to be associated with the Alpha Persei cluster, whose age is more like ~90 Myr (Stauffer, *et al*. 1999). De Zeeuw, *et al*. (1999) did *not* select either γ Cas (HIP 4427) or HR 266 (HIP 4440) as members of the Cas-Tau group. Only two purported members of Cas-Tau from de Zeeuw, *et al*. (1999) lie within 5 deg (HD 5409 and HR 342), however they appear to be background (~340 pc) and foreground (~124 pc) stars, respectively. Neither HD 5409 nor HR 342 appears to share the motion of the γ Cas system, nor lie within its estimated tidal radius. De Zeeuw, *et al*. (1999) estimates the space velocity of Cas-Tau to be (U,V,W) = (-13.2, -19.7, -6.4 km/s). Given the rarity of early B-type stars in the field, and their short lifetimes, plus the similarities in position, distance, and velocity between the γ Cas and Cas-Tau association (only ~4 km/s mismatch), it seems likely that the γ Cas system is somehow related to the Cas-Tau association.

Cas-Tau has relatively few early B-type stars, with the hottest members among the de Zeeuw et al. (1999) Hipparcos membership being of spectral type B1.5 (1 Per and Phi Per). It is possible that the B0.5IVe star γ Cas is a blue straggler, having been disrupted to its near -critical rotational speed by interaction(s) with member (s) from its evaporating cluster. With ~6 or ~7 members with mass >1 $\mathcal{M}_{\rm Sun}$, and assuming a typical initial mass function (Kroupa, *et al*. 2001), the γ Cas protocluster likely had at least ~70 stellar members. If the γ Cas and HR 266 subsystems have close passes, the perturbations among the components could account for the high eccentricity of the tight subsystem HR 266 Ba+Bb (e = 0.415, P = 4.24 day). Among 677 spectroscopic binaries in the SB9 catalog (Pourbaix, *et al*. 2004) with orbital periods within ±50% of 4.24 day, one finds only 17 (2.5%) with eccentricities exceeding 0.4, making HR 266 Ba+Bb a ~2σ outlier in terms of eccentricity compared to comparably tight binaries.

The γ Cas+HR 266 septuplet may constitute one of the highest-N multiple systems known. The evolution of disintegrating young clusters into high-order multiples like this system may provide some context for the dynamical conditions which spawn the classic Be star phenomena.

Acknowledgements

Figure 1 was generated using SkyView. I acknowledge the use of NASA's *SkyView* facility (http://skyview.gsfc.nasa.gov) located at NASA Goddard Space Flight Center. DSS1 blue imagery was taken by CalTech with compression and distribution by Space Telescope Science Institute. DSS2 blue and red data were taken by ROE, AAO, and CalTech, with compression and distribution by Space Telescope Science Institute. This research has made use of the SIMBAD database and Vizier catalogue access tool operated at CDS, Strasbourg, France. Thanks are extended to Brian Mason and Bill Hartkopf for comments.

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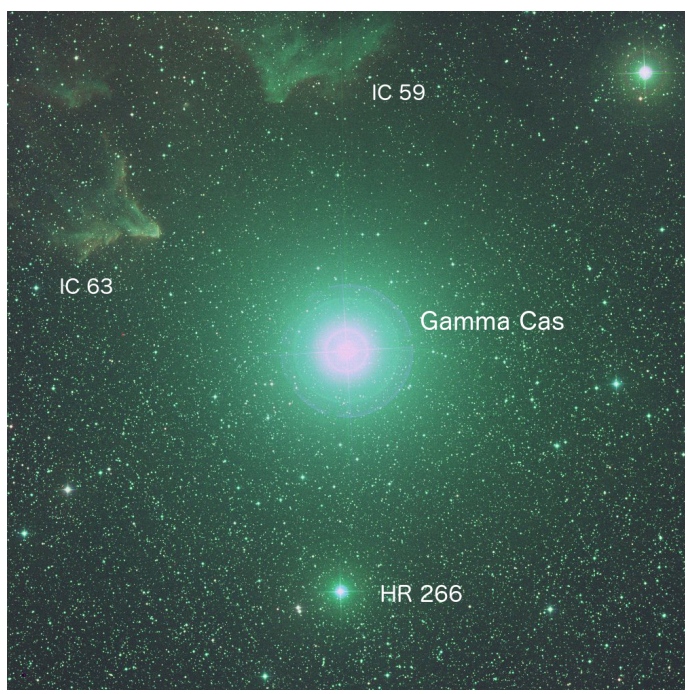

Figure 1. One degree field of view image of γ Cas and vicinity generated using Skyview. The image is RGB using DSS2 red (red), DSS1 blue (green), and DSS2 blue (blue). At d = 168 pc, 1 degree equals about 2.9 pc.

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