Feedback from \(\gamma\) Cassiopeiae: Large Expanding Cavity, Accelerating Cometary Globules, and Peculiar X-Ray Emission

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Abstract

We present wide-field multiwavelength observations of \(\gamma\) Cassiopeiae (or \(\gamma\) Cas for short) in order to study its feedback toward the interstellar environment. A large expanding cavity is discovered toward \(\gamma\) Cas in the neutral hydrogen (H\(I\)) images at a systemic velocity of about \(-10\) km s\(^{-1}\). The measured dimension of the cavity is roughly \(2.0 \times 1.4\) (or \(6.0\) pc \(\times 4.2\) pc at a distance of 168 pc), while the expansion velocity is \(\sim 5.0 \pm 0.5\) km s\(^{-1}\). The \(\text{CO}\) observations reveal systematic velocity gradients in IC 63 (\(-20\) km s\(^{-1}\) pc\(^{-1}\)) and IC 59 (\(-30\) km s\(^{-1}\) pc\(^{-1}\)), two cometary globules illuminated by \(\gamma\) Cas, proving fast acceleration of the globules under stellar radiation pressure. The gas kinematics indicate that the cavity is opened by strong stellar wind, which has high potential to lead to the peculiar X-ray emission observed in \(\gamma\) Cas. Our result favors a new scenario that emphasizes the roles of stellar wind and binarity in the X-ray emission of the \(\gamma\) Cas stars.

Unified Astronomy Thesaurus concepts: Be stars (142); Gamma Cassiopeiae stars (635); Interstellar medium (847); Stellar wind bubbles (1635)

1. Introduction

\(\gamma\) Cas is the prototype of Be stars (Secchi 1866; Rivinius et al. 2013) and is also one of the most studied stars in the sky (see, e.g., Poeckert & Marlborough 1978; Henrichs et al. 1983; Stee et al. 1995; Smith & Robinson 1999). It is a bright B0.5 IVe star located at a distance of 168 \(\pm 4\) pc from the Sun (van Leeuwen 2007). Radial velocity (RV) observations indicate that \(\gamma\) Cas is a binary system with an orbital period of \(\sim 203.5\) days (Harmanec et al. 2000; Nemravová et al. 2012). The primary stellar mass is estimated to be \(\sim 15\) M\(_{\odot}\), from its effective temperature (Harmanec et al. 2000), while the companion is suggested to be a white dwarf (Harmanec et al. 2000) or a helium star (Nemravová et al. 2012), with an estimated mass of about \(1.0\) M\(_{\odot}\).

It has been known that massive stars strongly influence their surrounding environment throughout their lifetime via strong UV radiation, stellar wind, and eventually a supernova explosion (see, e.g., Krumholz et al. 2014; Dale 2015). Previous observations toward the interstellar environment of \(\gamma\) Cas focused on IC 63 and IC 59, two cometary globules brightened by \(\gamma\) Cas (e.g., Blouin et al. 1997; Karr et al. 2005), which are located to the northeast (IC 63) and north (IC 59) of \(\gamma\) Cas, respectively. Both IC63 and IC59 are also associated with S185 (see Sharpless 1959), which is a bright H\(II\) region with a shell to the northeast of \(\gamma\) Cas (see, e.g., Sun et al. 2007). The two globules were well-studied, in order to understand the physical and chemical effects from stellar UV radiation (see, e.g., Jansen et al. 1994; Andersson et al. 2013; Andrews et al. 2018), as well as the magnetic field structure due to radiative grain alignment (see Soam et al. 2017, 2021).

In this work, we present wide-field multiwavelength images toward \(\gamma\) Cas, based on the observational data obtained from the neutral hydrogen (H\(I\)) \(4\alpha\) survey (HI4PI; see HI4PI Collaboration et al. 2016) and the CO Galactic plane survey conducted with the Purple Mountain Observatory (PMO) 13.7 m millimeter-wavelength telescope. Complementary images from the full-sky H\(\alpha\) map (Finkbeiner 2003) and the all-sky survey by the Wide-field Infrared Survey Explorer (WISE; Wright et al. 2010) are also used for comparisons with the H\(I\) and CO line data.

2. Observations and Data Reduction

2.1. HI4PI H\(I\) Data

We retrieved the H\(I\) line data from the HI4PI survey for the \(\gamma\) Cas region. The HI4PI survey is based on data from the recently completed first coverage of the Effelsberg-Bonn H\(I\) Survey (EBHIS; Winkel et al. 2016) and from the third revision of the Galactic All-Sky Survey (GASS; Kalberla & Haud 2015). The HI4PI survey toward the northern sky was performed with the Effelsberg 100 m telescope in Germany and the southern sky performed with the 64 m Parkes radio telescope in Australia. The GASS and EBHIS data were reduced by the two survey groups independently (see, e.g., Kalberla & Haud 2015 for GASS and Winkel et al. 2016 for EBHIS, respectively). After detailed comparisons and analyses, the two data sets were merged together with the same angular and spectral resolutions. The released HI4PI data have a velocity resolution of \(\sim 1.29\) km s\(^{-1}\) and an angular resolution of \(\sim 16'2\), while the typical rms noise of the line data is about 43 mK. For more details, we refer to the HI4PI survey introduction paper (see HI4PI Collaboration et al. 2016). Figure 5 in the Appendix A shows the HI4PI H\(I\) line velocity channel maps toward \(\gamma\) Cas.
2.2. CO Observations and Data Reduction

The CO(1−0) line observations toward the γ Cas region is part of the Milky Way Imaging Scroll Painting (MWISP) project for investigating the nature of the molecular gas along the northern Galactic plane (with Galactic latitude $|b| \leq 5^\circ$), using the PMO 13.7 m millimeter-wavelength telescope at the Delingha station in Qinghai, China (see, e.g., Su et al. 2019). The CO observations were made from 2011 November to 2020 February. The nine-beam Superconducting Spectroscopic Array Receiver (SSAR; Shan et al. 2012) worked as the front end in sideband separation mode. Three CO(1−0) lines were simultaneously observed, $^{13}$CO and C$^{18}$O at the upper sideband (USB) and two other lines, $^{12}$CO and C$^{18}$O, at the lower sideband (LSB). The total of the pointing and tracking errors is about 5″, and the half-power beamwidth (HPBW) is $\sim 55″$ (1″=10 km s$^{-1}$). A fast Fourier transform (FFT) spectrometer with a total bandwidth of 1000 MHz and 16,384 channels was used as the back end. The corresponding velocity resolutions were $\sim 0.16$ km s$^{-1}$ for the $^{12}$CO line and $\sim 0.17$ km s$^{-1}$ for both the $^{13}$CO and C$^{18}$O lines. More details about the PMO 13.7 m telescope system are described in the telescope status reports.\footnote{See http://www.radioast.cnsi.edu.cn/zhutangtaibaoqg.php.}

After removing bad channels and abnormal spectra, and correcting the first-order (linear) baseline fitting, the data were regressed into standard FITS files with a pixel size of $30′′ \times 30′′$ (approximately half of the beam size). The average rms noises of all final spectra are about 0.5 K for $^{12}$CO and about 0.3 K for $^{13}$CO and C$^{18}$O. Finally, we mosaicked the data cubes toward the γ Cas region to analyze the morphology and physical properties of molecular gas. Figures 6 and 7 in Appendix A show the $^{12}$CO line velocity channel maps toward γ Cas.

3. Results and Discussion

3.1. A Large Expanding Cavity toward γ Cas

Long-term (over 6000 days or 16.84 yr) RV monitors of γ Cas showed a spread of velocities in an approximate range of $-17$ to $-1$ km s$^{-1}$ in the local standard of rest (LSR) frame (see Nemravová et al. 2012). Taking an average of the RV measurements, the systemic velocity of γ Cas was estimated to be $-10$ km s$^{-1}$, which is consistent with the systemic velocities derived after the epoch of HJD 245 000 (Nemravová et al. 2012; see also Pollmann 2016). After checking the HI-4PI line maps toward γ Cas, we find a cavity within the measured RV range of γ Cas, which is most prominent at its systemic velocity (i.e., $-10$ km s$^{-1}$). Figure 1(a) shows the H I intensity image toward γ Cas, integrated between $-13.0$ and $-7.0$ km s$^{-1}$. The cavity is extended in the east–west direction. We note that no other massive OB star is found within the cavity region in the Galactic local arm, except γ Cas.\footnote{After checking the SIMBAD Astronomical Database (see http://simbad.u-strasbg.fr/simbad/), another Be star, HD 4931 ($l = 123°03′34″$, $b = -2°78′72″$), is seen toward the H I cavity. Its radial velocity is $\sim 52.2$ km s$^{-1}$, and observed parallax is 0.5541 mas (or a distance of 1800 pc) by the Gaia satellite.}

Figure 1(b) shows the wide-field H$\alpha$ image toward γ Cas. In the H$\alpha$ image, an extended ionized hydrogen emission nebula is seen around γ Cas, with a bright shell toward the east and northeast of γ Cas. This bright shell was also seen in the $\lambda 6$ cm radio continuum observations (Sun et al. 2007). The large extended H$\alpha$ emission nebula, with a radius of $\sim 1′8-2′0$, was suggested to represent the Strömgren sphere produced by the photoionization from γ Cas (see Karr et al. 2005 and Appendix B). It is widely known that massive stars experience strong mass loss in the form of winds, which will sweep up the interstellar medium (ISM) and create low density wind-blown cavities surrounded by dense shells (see, e.g., Weaver et al. 1977; Freyer et al. 2003). The comparison between the H I and H$\alpha$ images shows that the H I cavity discovered toward γ Cas is located within the large H$\alpha$ nebula caused by strong photoionization, which is in good agreement with the classical picture for the feedback from massive stars.\footnote{In the classical picture, the radiation field of a massive star first dissociates the interstellar gas and forms a photodissociation region of neutral hydrogen. Subsequently, the Lyman continuum photons of the star ionize the H I gas and produce an H II region that expands into the neutral ambient medium. Then, a fast stellar wind creates shocks that form a wind-blown cavity filled with hot plasma, which expands into the H II region (see, e.g., Weaver et al. 1977 and Freyer et al. 2003 for more details).}

Therefore, we suggest that the H I cavity is produced by stellar wind from γ Cas.

Figure 2 shows the H I position–velocity (PV) diagrams along the routings across the cavity toward γ Cas (see the routings shown in Figure 1(a)). Cavity-like PV patterns are detected in the various directions, indicating that the cavity is expanding. As seen in the diagrams, the cavity-like PV patterns could be well fitted by ellipses, with the position and velocity radii representing the projected radii and expanding velocities of the cavities, respectively. The measured expanding velocity of the cavity is roughly $5.0 \pm 0.5$ km s$^{-1}$, while the radii of the cavity, depending on the azimuths, range from $\sim 0′7$ (or $\sim 2.1$ pc at distance of 168 pc) to $\sim 1′0$ (~3.0 pc). Using the Equation (3) in Churchwell et al. (2006), the eccentricity of the cavity is calculated to be roughly 0.71, which is a typical value in the Galactic cavity/bubble statistics (see, e.g., Churchwell et al. 2007). This kind of extended structure is generally explained by nonuniform ambient ISM into which the cavities are expanding and/or anisotropic stellar wind and radiation field.\footnote{To the west of the γ Cas H I cavity is another cavity-like structure in the H I images (see Figure 1(a)). This cavity may be opened by other bright stars in the region. In this work we focus on the H I cavity toward γ Cas.}

Adopting the standard method (Weaver et al. 1977), the value of the mechanical luminosity (the kinetic energy of stellar wind per unit time) of the wind ($L_{wind}$) can be calculated by

$$L_{wind} \approx \frac{1}{3} \left( \frac{n_{gas}}{\text{cm}^{-3}} \right) \left( \frac{R_c}{\text{pc}} \right)^2 \left( \frac{V_c}{\text{km s}^{-1}} \right)^3 \times 10^{30} \text{ erg s}^{-1},$$

in order to excavate a cavity with a radius of $R_c$ and an expansion velocity of $V_c$ within a cloud with a density of $n_{gas}$. The density $n_{gas}$ can be measured from the radius and column density of the cavity by

$$n_{gas} = \frac{3N_{shell}}{R_c},$$

where $N_{shell}$ is the column density observed at the shell of the cavity. Based on the H I line observations, the density $n_{gas}$ of the hydrogen gas surrounding γ Cas is measured to be $\sim 150$ cm$^{-3}$. With the radii and expansion velocity measured above, the $L_{wind}$ is then estimated to be $\sim (3.9 \pm 1.0) \times 10^{34}$ erg s$^{-1}$ for the γ Cas cavity. By the relation of $t_{kin} = \frac{6 R_c}{27 \frac{R_c}{\text{km s}^{-1}} V_c}$, the kinetic timescale $t_{kin}$ of the wind needed for opening such a cavity is estimated to be $\sim (3.0 \pm 0.5) \times 10^6$ yr. The mechanical luminosity of the wind is also defined by

$$L_{wind} = \frac{1}{2} MV_{wind}^2,$$

where $M$ and $V_{wind}$ are the mass-loss rate and
**Figure 1.** (a) Wide-field HI4PI HI intensity images toward $\gamma$ Cas, integrated between $-13.0$ and $-7.0$ km s$^{-1}$. The contours represent the emission at 200, 220, 240, 270, and 300 K km s$^{-1}$, and then increase by steps of 40 K km s$^{-1}$. The red stellar symbol marks the position of $\gamma$ Cas. White dashed arrow lines show cutting routings to extract the position–velocity diagrams. Yellow squares show the positions of IC 63 and IC 59 globules, respectively. Blue beam shows the angular resolution ($16''$) of the HI4PI data. (b) The H$\alpha$ image toward $\gamma$ Cas. The yellow dashed ellipse shows the cavity found in the HI images. The H$\alpha$ contour (gray) represents the emission at 18 Rayleighs (Rayleigh = $10^6$/4$\pi$ photons cm$^{-2}$ s$^{-1}$ sr$^{-1}$), outlining a large Strömgren sphere with a radius of $\sim$1°–2°. Yellow circles mark the positions of other H II regions in the field. These H II regions, such as S173 ($\sim$35 km s$^{-1}$), S177 ($\sim$34 km s$^{-1}$), and S187 ($\sim$15 km s$^{-1}$), have different systemic velocities (see Blitz et al. 1982) and are located much farther away than S185 (associated with $\gamma$ Cas).

**Figure 2.** The H I position–velocity diagrams cutting across the cavity toward $\gamma$ Cas. In all the panels, the red stellar symbol marks the position of $\gamma$ Cas. The blue rectangle shows the angular resolution ($16''$) and velocity resolution (1.29 km s$^{-1}$) in the HI4PI observations. The H I contours start at 30 K and then increase in steps of 5 K (where 1$\sigma$ $\sim$ 0.2 K). The yellow dashed ellipses show fitting results toward the cavity-like patterns seen in the diagrams.
velocity of the wind, respectively, which can be measured through optical and/or infrared spectroscopies. For \( \gamma \) Cas, the measured stellar wind is strong, with a fast velocity of \( \sim 1500-1800 \text{ km s}^{-1} \) (Smith & Robinson 1999) and a mass-loss rate of \( 5 \times 10^{-5} \text{ M}_\odot \text{ yr}^{-1} \) (Stee et al., 1995), and the calculated \( L_{\text{wind}} \) is \( \sim 3.6-5.1 \times 10^{34} \text{ erg s}^{-1} \). Therefore, the mechanical luminosities of the wind observed from cavity gas kinematics and stellar spectroscopies are consistent with each other.

3.2. The Cometary Globules in Acceleration

Both observational and numerical studies suggested that molecular gas could be formed in dense shells of large cavities/bubbles created by massive stars (see, e.g., Dawson 2013; Inutsuka et al. 2015 and references therein). Numerical studies suggest that the timescale for accumulating a CO molecular cloud (\( t_{\text{acc}} \)) from H1 atomic gas behind shock waves can be estimated by \( n v \gtrsim 20(20 \text{ Myr}) / t_{\text{acc}} \text{ cm}^{-3} \text{ km s}^{-1} \), where \( n \) is the H1 gas density and \( v \) is the velocity of the shock wave (see Bergin et al. 2004). Given \( n = 150 \text{ cm}^{-3} \) (see above) and assuming a typical sound speed of 10 km s\(^{-1}\), the estimated \( t_{\text{acc}} \) is roughly 1.3–2.7 \times 10^5 yr (when shock velocity \( v \) is in the range of 10–20 km s\(^{-1}\)), which is comparable to the kinetic age of the \( \gamma \) Cas cavity (\( t_{\text{kin}} \sim 3.0 \pm 0.5 \times 10^5 \text{ yr} \); see above).

Figure 3(a) shows the wide-field MWISP CO intensity image toward \( \gamma \) Cas, integrated between \(-13.0 \text{ and } -7.0 \text{ km s}^{-1} \) (see also the CO velocity channel map in Appendix A). A few CO clumps are detected in the dense shell of the H1 cavity toward \( \gamma \) Cas (see Figure 3(a)). After inspecting the CO velocity fields, we find in these clumps systematic velocity gradients toward \( \gamma \) Cas (see Figure 3(b)), and measured velocity gradients in these clumps range from \( -4 \text{ to } -7 \text{ km s}^{-1} \). This suggests that these clumps are affected by the stellar wind from \( \gamma \) Cas. We further check the H1-CO spectra from these clumps to search for the signature of H1 narrow self-absorption (HINSA). HINSA is generally accepted as evidence for the presence of cold H1 gas, which suggests the formation phase of molecular gas, when HINSA is spectrally and spatially coincident with molecular line emission (see, e.g., Li & Goldsmith 2003; Goldsmith & Li 2005). Nevertheless, no clear HINSA signature is found in these clumps (see Figure 3(c)). Higher angular resolution and sensitivity H1 and CO line observations are needed to further study whether there is molecular gas formation in the shell of the \( \gamma \) Cas cavity.

Figure 4(a) shows the MWISP \(^{12}\text{CO}\) line emission images (contours) toward IC 63 and IC 59, plotted on the WISE 12 \mu\text{m} image. As seen in the figure, strong CO gas emission is detected from both the IC 63 and IC 59 globules, at the velocity range between \(-1 \text{ and } 4 \text{ km s}^{-1} \) (see also CO velocity channel map in Appendix A). It is of interest to note that the peak CO emission velocities of IC 63 (\( \sim 0.5 \text{ km s}^{-1} \)) and IC 59 (\( \sim 1.0 \text{ km s}^{-1} \)) are \( \sim 10 \text{ km s}^{-1} \) offset from the systemic velocity of \( \gamma \) Cas (\( \sim 10 \text{ km s}^{-1} \)). Nevertheless, the velocity offsets are actually expected, as cometary globules should be accelerated by the radiation of its exciting star (see, e.g., Lefloch & Lazareff 1994). For \( \gamma \) Cas (a bright B0.5IVe star), the estimated velocity difference due to the radiation acceleration is approximately \( 10 \text{ km s}^{-1} \) between cometary globules and the exciting source (Soam et al., 2017), which is the exact velocity offset seen in the CO and H1 observations toward \( \gamma \) Cas.

In the MWISP \(^{12}\text{CO}\) observations, clear and systematic velocity gradients are revealed along the IC 63 (\( \sim 20 \text{ km s}^{-1} \) pc\(^{-1}\)) and IC 59 (\( \sim 30 \text{ km s}^{-1} \) pc\(^{-1}\)) globules, proving the acceleration of the two globules. The observed velocity gradients in the two globules are larger than those measured in the CO clumps around the cavity (see above), and also much larger than those observed in other cometary globules, such as CG 7S (\( \sim 3 \text{ km s}^{-1} \) pc\(^{-1}\); Lefloch & Lazareff 1995), IC 1369 (\( \sim 5.5 \text{ km s}^{-1} \) pc\(^{-1}\); Sugitani et al. 1997), and the Eagle Nebula’s fingers (\( \sim 1.7 \text{ km s}^{-1} \) pc\(^{-1}\); White et al. 1999). In this context, we consider that the IC 63 and IC 59 cometary globules, under strong radiation pressure from \( \gamma \) Cas, were preexisting before the H1 cavity.

3.3. The Peculiar X-Ray Emission from \( \gamma \) Cas

\( \gamma \) Cas was also one of the first extra solar X-ray sources discovered (Jernigan 1976; Mason et al. 1976). However, its X-ray emission is significantly different from that observed from the bulk of Be stars (see, e.g., a review by Smith et al. 2016 and references therein). Galactic X-ray surveys have found a growing number of Be stars with similar X-ray properties and sharing a narrow range of characteristics (Smith et al. 2016; Nazé et al. 2020), such as hard X-ray emission, multiple thermal components, high variability, and moderated X-ray luminosity (\( \sim 10^{31}-10^{32} \text{ erg s}^{-1} \)). The origin of the peculiar X-ray emission of the \( \gamma \) Cas stars is one of the puzzles in X-ray stellar astrophysics, which is important to understand massive star evolution and the energy budget of the Galaxy. Two competing scenarios, magnetic star-disk interaction (e.g., Motch et al. 2015) and accretion onto compact companion (e.g., Hamaguchi et al. 2016), have been suggested to explain these outstanding features, but both provide imperfect matches with observations (Nazé et al. 2017, 2019; Langer et al. 2020).

Considering that \( \gamma \) Cas stars are close binaries, a recent new scenario suggests that the X-ray emission originates from the interaction between the wind from the companion star (a helium star or white dwarf) and the Be star disk and/or wind (see Langer et al. 2020). For \( \gamma \) Cas, the estimated mechanical luminosity of the wind (\( \sim 3.9 \times 10^{14} \text{ erg s}^{-1} \); see above) is much larger than its X-ray luminosity \( L_X \) observed at the band of \( \sim 0.5-10 \text{ keV} \) (\( \sim 8.5 \times 10^{32} \text{ erg s}^{-1} \) or \( \sim 2\% \) of the mechanical luminosity of the wind). Recent studies based on the X-ray surveys by the XMM-Newton satellite (covering 0.2–2 keV) suggest a relation of

\[
\log L_X = 23.6 \pm 3.8 + (0.3 \pm 0.1) \log L_{\text{wind}}
\]

for spectroscopically identified Galactic O stars (Nebot & Oskinova 2018). For a comparison, an earlier survey by the Einstein satellite (covering 0.2–4 keV) suggested another relation of

\[
\log L_X = 0.51^{+0.09}_{-0.11} \log L_{\text{wind}} + 14.5^{+2.0}_{-3.3}
\]

for O stars (Sciortino et al. 1990). Assuming that the relations also work for Be stars (note that the parameter space in these relations is large), the estimated \( L_X \) ranges between roughly \( 1.4 \times 10^{32} \text{ erg s}^{-1} \) (Einstein relation) and \( 9.5 \times 10^{33} \text{ erg s}^{-1} \) (Newton relation) for \( \gamma \) Cas. The estimated values are comparable with those detected in the X-ray observations. This indicates that the mechanical luminosity of the wind \( L_{\text{wind}} \) is sufficient to account for the observed X-ray luminosity in \( \gamma \) Cas (see also the discussion in

\footnote{In this scenario, magnetic field anchored in the rotating Be star interacts with its Keplerian circumstellar disk. Reconnection events accelerate particles that produce X-rays when impacting the disk or the photosphere.}

\footnote{In binaries, accretion of matter onto a compact object, likely a white dwarf, could power strong X-ray luminosity.}
Langer et al. 2020), although the accurate conversion efficiency between \( L_{\text{wind}} \) and \( L_X \) is unclear.

In the \( \gamma \) Cas binary system, the interaction between the primary and secondary stars was suggested by bow-shock nebula detected in the WISE 22 μm images (Bodensteiner et al. 2018; Langer et al. 2020). Therefore, the interaction between the winds from the primary and secondary stars can be expected in turn. Numerical studies have shown that the interaction between the winds in massive binary systems will produce much harder X-ray emission than that from single massive stars (Rauw & Nazé 2016; Pittard & Dawson 2018). Furthermore, wind–wind and wind–disk interactions in binary systems will result in multiple thermal components detected in the X-ray observations (see Hamaguchi et al. 2016; Langer et al. 2020). The short variability of the X-ray luminosity

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**Figure 3.** (a) The HI4PI HI intensity image, overlapped with the MWISP \(^{12}\)CO contours (blue). The integrated velocity range is \([-13, -7]\) for both the HI and CO lines. The HI contours (black) represent the emission at 200, 210, 220, and 235 K km s\(^{-1}\), respectively. The \(^{12}\)CO contours start from the 5σ level and then increase by steps of 5σ (1σ \(\sim\) 0.6 K km s\(^{-1}\)). The yellow dashed rectangles show the extents of the CO clumps around the cavity. (b) The MWISP \(^{12}\)CO velocity fields of the clumps. The unit of the scale bar is km s\(^{-1}\). The arrow shows the direction toward \( \gamma \) Cas for individual clumps. (c) The HI4PI HI and MWISP \(^{13}\)CO spectra of the clumps, sampled at the positions marked by yellow circles in panel (a).
(in the timescale of seconds or minutes) seen in the $\gamma$ Cas stars can be explained by the high intrinsic instability of the wind, while the phase-dependent variability (hours or days) may be due to changes in the stellar separation, wind absorption, and/or stellar occultation (Rauw & Nazé 2016; Pittard & Dawson 2018).

4. Summary

We present wide-field H14PI H1 and MWISP CO images toward $\gamma$ Cas, in order to study its feedback toward the interstellar environment. A large expanding cavity, with a
dimension of $\sim 2.0 \times 1.4$ (or $6.0 \, \text{pc} \times 4.2 \, \text{pc}$), is discovered toward $\gamma$ Cas in the HI images. The measured expansion velocity is roughly $5.0 \pm 0.5 \, \text{km s}^{-1}$. The comparison between multiwavelength images indicates that the cavity is opened by strong stellar wind from $\gamma$ Cas, and the estimated mechanical luminosity of the wind is $\sim (3.9 \pm 1.0) \times 10^{34} \, \text{erg s}^{-1}$. The CO observations show no clear molecular cloud formed on the dense shell of the cavity. Furthermore, strong CO emission is detected from IC 63 and IC 59, the two cometary globules illuminated by $\gamma$ Cas. The systematic velocity gradients ($\sim 20$–$30 \, \text{km s}^{-1} \, \text{pc}^{-1}$) are observed in the two globules, proving the fast acceleration under the pressure from the stellar radiation. We consider that stellar wind from $\gamma$ Cas has high potential to lead to its observed peculiar X-ray emission. Our result favors a recent new scenario that emphasizes the roles of stellar wind and binarity in the X-ray emission for the $\gamma$ Cas stars.

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Appendix A

The HI4PI HI and MWISP CO Maps of $\gamma$ Cas

Figure 5 shows the HI4PI line channel map toward $\gamma$ Cas at the velocity range from $-20$ to $+5 \, \text{km s}^{-1}$, where detailed HI gas structure and kinematics toward $\gamma$ Cas can be seen. Figure 6 shows the MWISP CO line emission within the velocity range from $-17$ to $+7 \, \text{km s}^{-1}$, presenting the details of molecular gas surrounding $\gamma$ Cas. Figure 7 shows the CO enlarged views toward the IC 63 and IC 59 globules.
Figure 5. The HI4PI H I line velocity channel maps toward γ Cas. The unit of the scale bar is K. For all panels, red stellar symbol marks the position of γ Cas. The LSR velocity is written in the top left corner of each panel (in km s$^{-1}$), and the systemic velocity of γ Cas is approximately $-10$ km s$^{-1}$. 
Figure 6. The MWISP $^{12}$CO line velocity channel maps toward $\gamma$ Cas. The unit of the scale bar is K km s$^{-1}$. For all panels, the red star symbol marks the position of $\gamma$ Cas. The integrated velocity range is written in the bottom right corner of each panel (in km s$^{-1}$). The red dashed ellipse shows the cavity found in the HI observations. The blue squares show the extents of the IC 63 and IC 59 globules (see below Figure 7).
Appendix B

The Strömgren Sphere Produced by $\gamma$ Cas

After the formation of massive stars in the molecular cloud, the massive stars will form bright H II regions through photoionization, which is first introduced in detail by Strömgren (1939). If a source of $Q_{\text{H}}$ ionizing photons per second ignites in a cloud with an initial number density of $n_0$ atoms cm$^{-3}$, the initial number density of ions $n_i$ will be equal to $n_0$. If the cloud is pure hydrogen and completely electrically neutral, then the number density of electrons $n_e$ will be equal to the number density of ions, that is, we have $n_e = n_i = n_0$.

When the ionization source is formed, the ions will recapture electrons in the ionization region and recombine to the bound state of the atom, which will consume part of the photons. Finally, the photons consumed by recombination and those produced by the ionization source are balanced, and no more central gas is ionized. In this state, the Strömgren sphere in the ionization region is formed, and the radius of the Strömgren sphere can be expressed as

$$R_S = \left( \frac{3Q_{\text{H}}}{4\pi \alpha_B n_0^2} \right)^{\frac{1}{3}},$$

where $\alpha_B = 2.6 \times 10^{-13} (10^4 \text{K}/T)^{0.7} \text{cm}^3 \text{s}^{-1}$ is the recombination rate at the ionized gas temperature of $T$. For $\gamma$ Cas (a bright B0.5 I Ve star), we take $7.9 \times 10^{47}$ photons s$^{-1}$ as the stellar ionizing photon rate (see Vacca et al. 1996), while the temperature of the ionized gas is assumed to be 10,000 K. The number density is estimated to be $\sim 150 \text{cm}^{-3}$ based on the H I observations (see Section 3.1). Then, the estimated radius of the Strömgren sphere $R_S$ is roughly 1.0 pc or $\sim 0^\circ.33$ at the distance of 168 pc.

It is also known that the Strömgren sphere is expanding during the evolution of the ionization source. This process was first studied by Spitzer (1978), who derived the well-known expansion relation

$$R(t) = R_S \left( 1 + \frac{7c_{\text{HII}}t}{4R_S} \right)^{\frac{1}{2}},$$

where $c_{\text{HII}}$ is the sound speed in the ionized gas and $t$ is the evolution time of the H II region. In the calculations, the sound speed $c_{\text{HII}}$ is generally assumed to be 10 km s$^{-1}$. The evolution time of the H II region is still uncertain for $\gamma$ Cas. Assuming $t = 1 \text{ Myr}$ (about 3 times of the dynamical age of the H I cavity, i.e., $\sim 3.0 \times 10^5$ yr; see Section 3.1), the radius of the evolved Strömgren sphere is $\sim 5.3$ pc (or $\sim 1^\circ.8$), which is consistent with the result seen in the H$\alpha$ images (see Figure 1(b)).

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Figure 7. The enlarged MWISP $^{12}$CO line velocity channel maps toward IC 63 and IC 59. The unit of the scale bar is K km s$^{-1}$. For all panels, red star symbol marks the position of $\gamma$ Cas. The integrated velocity range is written in the top left corner of each panel (in km s$^{-1}$). The CO contours start from 1.0 K km s$^{-1}$ ($1\sigma \sim 0.25$ K km s$^{-1}$) and then increase by steps of 1.0 K km s$^{-1}$.
References

Andersson, B.-G., Piirola, V., De Buizer, J., et al. 2013, ApJ, 775, 84
Andrews, H., Peeters, E., Tielens, A. G. G. M., et al. 2018, A&A, 619, A170
Bergin, E. A., Hartmann, L. W., Raymond, J. C., et al. 2004, ApJ, 612, 921
Blitz, L., Fich, M., & Stark, A. A. 1982, ApJS, 49, 183
Blouin, D., McCutcheon, W. H., Dewdney, P. E., et al. 1997, MNRAS, 287, 455
Bodensteiner, J., Baade, D., Greiner, J., et al. 2018, A&A, 618, A110
Churchwell, E., Povich, M. S., Allen, D., et al. 2006, ApJ, 649, 759
Churchwell, E., Watson, D. F., Povich, M. S., et al. 2007, ApJ, 670, 428
Dale, J. E. 2015, NewAR, 68, 1
Dawson, J. R. 2013, PASA, 30, e025
Finkbeiner, D. P. 2003, ApJS, 146, 407
Freyer, T., Hensler, G., & Yorke, H. W. 2003, ApJ, 594, 888
Goldsmith, P. F., & Li, D. 2005, ApJ, 622, 938
Hamaguchi, K., Oskinova, L., Russell, C. M. P., et al. 2016, ApJ, 832, 140
Hamann, P., Habuda, P., Stefl, S., et al. 2000, A&A, 364, L85
Henrichs, H. F., Hammerschlag-Hensberge, G., Howarth, I. D., et al. 1983, ApJ, 268, 807
HI4PI Collaboration, Ben Bekhti, N., Fliér, L., et al. 2016, A&A, 594, A116
Inutsuka, S.-ichiro, Inoue, T., Iwasaki, K., et al. 2015, A&A, 580, A49
Jansen, D. I., van Dishoeck, E. F., & Black, J. H. 1994, A&A, 282, 605
Jernigan, J. G. 1976, IAUC, 2900, 2
Kalberla, P. M. W., & Haud, U. 2015, A&A, 578, A78
Karr, J. L., Noriega-Crespo, A., & Martin, P. G. 2005, AJ, 129, 954
Krumholz, M. R., Bate, M. R., Arce, H. G., et al. 2014, in Protostars and Planets VI, ed. H. Beuther et al. (Tucson, AZ: Univ. Arizona Press), 243
Langer, N., Baade, D., Bodensteiner, J., et al. 2020, A&A, 633, A40
Lebbec, B., & Lazareff, B. 1994, A&A, 289, 559
Lebbec, B., & Lazareff, B. 1995, A&A, 301, 522
Li, D., & Goldsmith, P. F. 2003, ApJ, 585, 823
Mason, K. O., White, N. E., & Sanford, P. W. 1976, Natur, 260, 690
Motch, C., Lopes de Oliveira, R., & Smith, M. A. 2015, ApJ, 806, 177

Nazé, Y., Motch, C., Rauw, G., et al. 2020, MNRAS, 493, 2511
Nazé, Y., Rauw, G., & Cazorla, C. 2017, A&A, 602, L5
Nazé, Y., Rauw, G., & Smith, M. 2019, A&A, 632, A23
Nebot, G.-M. A., & Oskinova, L. M. 2018, A&A, 620, A89
Nemravová, J., Harmanec, P., Koubský, P., et al. 2012, A&A, 537, A59
Pittard, J. M., & Dawson, B. 2018, MNRAS, 477, 5640
Poeckert, R., & Marlborough, J. M. 1978, ApJ, 220, 940
Pollmann, E. 2016, IBVS, 6169, 1
Rauw, G., & Nazé, Y. 2016, AdSpR, 58, 761
Rivinius, T., Carciofi, A. C., & Martayan, C. 2013, A&ARv, 21, 69
Sciortino, S., Vaiana, G. S., Hamden, F. R., Jr., et al. 1990, ApJ, 361, 621
Secchi, A. 1866, AN, 68, 63
Shan, W. L., Yang, J., Shi, S. C., et al. 2012, IITST, 2, 593
Sharpless, S. 1959, ApJS, 4, 257
Smith, M. A., Lopes de Oliveira, R., & Motch, C. 2016, AdSpR, 58, 782
Smith, M. A., & Robinson, R. D. 1999, ApJ, 517, 866
Soam, A., Andersson, B.-G., Straizys, V., et al. 2021, AJ, 161, 149
Soam, A., Maheswar, G., Lee, C. W., et al. 2017, MNRAS, 465, 559
Spitzer, L. 1978, Physical Processes in the Interstellar Medium (New York: Wiley)
Stee, P., de Araújo, F. X., Vakili, F., et al. 1995, A&A, 300, 219
Strömgren, B. 1939, ApJ, 89, 526
Su, Y., Yang, J., Zhang, S., et al. 2019, ApJS, 240, 9
 Sugitani, K., Morita, K.-I., Nakano, M., Tamura, M., & Ogura, K. 1997, ApJ, 486, 141
Sun, X. H., Han, J. L., Reich, W., et al. 2007, A&A, 463, 993
Vacca, W. D., Garmany, C. D., & Shull, J. M. 1996, ApJ, 460, 914
van Leeuwen, F. 2007, A&A, 474, 653
Weaver, R., McCray, R., Castor, J., Shapiro, P., & Moore, R. 1977, ApJ, 218, 377
White, G. J., Nelson, R. P., Holland, W. S., et al. 1999, A&A, 342, 233
Winkel, B., Kerp, J., Flöer, L., et al. 2016, A&A, 585, A41
Wright, E. L., Eisenhardt, P. R. M., Mainzer, A. K., et al. 2010, AJ, 140, 1868