Abstract

We present the detections of shocked molecular hydrogen (H$_2$) gas in near- and mid-infrared and broad CO in millimeter from the mixed-morphology supernova remnant (SNR) HB 3 (G132.7+1.3) using the Palomar Wide-field InfraRed Camera, the Spitzer GLIMPSE360 and Wide-field Infrared Survey Explorer (WISE) surveys, and the Heinrich Hertz Submillimeter Telescope. Our near-infrared narrow-band filter H$_2$ 2.12 μm images of HB 3 show that both Spitzer Infrared Array Camera and WISE 4.6 μm emission originates from shocked H$_2$ gas. The morphology of H$_2$ exhibits thin filamentary structures and a large scale of interaction sites between the HB 3 and nearby molecular clouds. Half of HB 3, the southern and eastern shell of the SNR, emits H$_2$ in a shape of a butterfly or W, indicating the interaction sites between the SNR and dense molecular clouds. Interestingly, the H$_2$ emitting region in the southeast is also co-spatial to the interacting area between HB 3 and the H II regions of the W3 complex, where we identified star-forming activity. We further explore the interaction between HB 3 and dense molecular clouds with detections of broad CO(3-2) and CO(2-1) molecular lines from the southern and southeastern shell along the H$_2$ emitting region. The widths of the broad lines are 8–20 km s$^{-1}$; the detection of such broad lines is unambiguous, dynamic evidence of the interactions between the SNR and clouds. The CO broad lines are from two branches of the bright, southern H$_2$ shell. We apply the Paris–Durham shock model to the CO line profiles, which infer the shock velocities of 20–40 km s$^{-1}$, relatively low densities of 10$^{3.4}$–$10^{4}$ cm$^{-3}$, and strong (>200 μG) magnetic fields.

Unified Astronomy Thesaurus concepts: CO line emission (262); Interstellar line emission (844); Supernova remnants (1667); Nebulae (1095); Interstellar medium (847); Line intensities (2084); Infrared telescopes (794); Collisional broadening (2083); Infrared dark clouds (787); Infrared observatories (791); Molecular physics (2058); Core-collapse supernovae (304)

Supporting material: data behind figure

1. Introduction

Interstellar shocks are ubiquitous in the interstellar medium (ISM) including supernova blast waves, jets, and outflows in protostars, and spiral arm density waves in galaxies. The shocks inject energy and momentum into the surrounding regions, and have a strong impact on the local physical conditions, the gas chemistry, and they regulate dust grains through sputtering and shattering. The interstellar gas dynamics is crucial for understanding the evolution of the ISM. The outflows of protostellar jets are shown to be able to clear material in the core, enough to cause termination of the infall phase, which affects SF efficiency in the cloud (Matzner & McKee 2000). The shocks influence the evolution of molecular clouds by injecting supersonic turbulence, and the resulting star-formation (SF) efficiency affects the SF rate in galaxies. Studying Galactic supernova shocks provides a relatively clean example of isolated systems. In contrast, shocks from protostars combine with many other phenomena due to strong UV radiation from the central source and additionally continuous fragmentations of molecular clouds may occur resulting in chains of star-forming clusters.

SF activity is frequently found in infrared dark clouds (Jackson et al. 2008; Kónyves et al. 2010; André et al. 2013). Turbulence may be a source of initiating SF through cloud fragmentation (Mac Low & Klessen 2004). What is the source of turbulence that may induce cloud collapse, such as observed in infrared dark clouds? Whether the observed sub-filaments are a result of the fragmentation process (Tafalla & Hacar 2015), or whether they first formed at the stagnation points of a turbulent velocity field and have been brought together by gravitational contraction on larger scales (Smith et al. 2016) is unclear. Shock waves are known to inject energy into the ISM. The presence of shocked gas (e.g., SiO) often observed from dense cores may be associated with turbulence.

Supernovae (SNe) play a key role in turbulence enhancement (Dib et al. 2006) and galactic wind acceleration in star-forming galaxies (SFGs; Veilleux et al. 2005). Galaxy formation models often include strong stellar feedback that predicts too high SF rates—a factor of 100 higher than the values observed (Muratov et al. 2015). Accounting for proper stellar feedback is essential to model galaxy formation, but the computation itself is challenging. A method of local box simulation with a vertical gravitational potential is used to study how SN feedback in a stratified galactic disk drives turbulence and launches galactic winds (Martizzi et al. 2016). Although, this method cannot yet
produce realistic or physical results, the goal is to better understand disk turbulence and galactic outflow feedback by SNe. This modeling attempt stresses the importance to understanding stellar feedback through SNe. Supernova remnants (SNRs) interacting with molecular clouds provide viable laboratories to study the effects of stellar feedback and the dynamic environment due to the shocks from the powerful explosions.

Signs of SNR interactions with molecular clouds include broad CO lines (van Dishoeck et al. 1993; Reach & Rho 1999; Rho et al. 2017), OH 1720 MHz masers (Frail et al. 1996; Yusef-Zadeh et al. 1999; Hewitt et al. 2008), shocked molecular hydrogen (H$_2$) emission (Rho et al. 2001; Neufeld & Yuan 2008), and so-called mixed-morphology SNRs with center-filled, thermal X-ray emission through evaporating clouds (Rho 1995; Rho & Petre 1998; Lazendic & Slane 2006; Pannuti et al. 2014). The 1720 MHz OH masers were detected from ~20 SNRs (Frail et al. 1996; Yusef-Zadeh et al. 1999; Hewitt et al. 2008), and molecular hydrogen H$_2$ cooling lines, as observed in IC 443 (e.g., Burton et al. 1988; Kokusho et al. 2020), W44, and W28 (Reach et al. 2005) and other SNRs using Spitzer GLIMPSE data (Reach et al. 2006). The clearest evidence for interaction between SNRs and molecular clouds is the detection of shock-excited molecular emission. In the millimeter and submillimeter, observations provide direct, unambiguous evidence of interaction when a broad (>6 km s$^{-1}$) line is detected, attributed to dynamic motion of shocked gas (Kilpatrick et al. 2016). Molecular broad lines are detected from IC 443 (van Dishoeck et al. 1993), 3C 391 (Reach & Rho 1999), W44 (Wootten 1977; Seta et al. 2004; Reach et al. 2005; Anderl et al. 2014), W28 (Arikawa et al. 1999; Reach et al. 2005), HB 21 (Koo et al. 2001; Shinn et al. 2010) and W51C (Koo & Moon 1997). Broad molecular CO lines are detected from the SNR G357.7+0.3 (Rho et al. 2017) and a few other SNRs (Kilpatrick et al. 2016).

HB 3 (G132.7+1.3) is a large (80$^\prime$ × 95$^\prime$) SNR with a radio spectral index of 0.5 (see Figure 1; Velusamy & Kundu 1974; Leahy et al. 1985; Landecker et al. 1987). A recent estimate of the radio spectrum index is 0.56 (Green 2007). We assume a distance of 1.95 kpc for HB 3 (Xu et al. 2006; Ruch et al. 2007), which is the same as that of the neighboring W3 complex, motivated by GLIMPSE and Wide-field Infrared Survey Explorer (WISE) imaging showing a direct interaction between the SNR HB 3 and the W3 complex (see Section 4). The optical emission also shows a shell structure, which is roughly circular in outline and brightest at the west and north (van der Bergh et al. 1973; D’Odorico & Sabbadin 1977; Fesen & Gull 1983; Fesen et al. 1995). HEAO-1 and the Einstein imaging proportional counter (IPC) detected X-ray emission of HB 3 (Leahy et al. 1985). The thesis first presented ROSAT PSPC observations by Rho (1995), and Rho & Petre (1998) suggested that HB 3 is a mixed-morphology SNR showing center-filled, thermal X-ray emission within a well-defined shell-like radio morphology as shown in Figure 1. Both of the ROSAT Position Sensitive Proportional Counter (PSPC) observations (see Rho & Petre 1998; Rho 1995) and Advanced Satellite for Cosmology and Astrophysics (ASCA) observations (Lazendic & Slane 2006; Urošević et al. 2007) show that the best-fit of X-ray spectra yielded a line-of-sight absorption $N_H = (3–9) \times 10^{21}$ cm$^{-2}$ and a temperature of $kT = 0.15–0.35$ keV. The age of HB 3 estimated from the X-ray temperature is (1.2–3.0) × 10$^4$ yr (see Section 3 for details).

HB 3 was suggested to have interactions with nearby clouds as deduced from H1 and CO observations (Landecker et al. 1987; Routledge et al. 1991). Velocity-resolved H1 cloud structures coincide with HB 3 and an H1 line profile shows a broad-line structure between ~120 and 20 km s$^{-1}$. However, since the line includes all materials in the line of sight toward HB 3, the direct interaction is still unclear. There are CO clouds at ~42 km s$^{-1}$ to the south of the SNR (Huang & Thaddeus 1986; Routledge et al. 1991) but no broad CO lines were detected. Katagiri et al. (2016) and Acero et al. (2016) present bright $^{13}$CO ($J = 1–0$) toward the HB 3 and the W3 complex, but still without detection of broad CO lines. Moreover, searching for OH masers toward HB 3 has been confusing due to the bright neighboring HII complex, and Koralesky et al. (1998) concludes that the masers seen in this direction are not collisionally excited by the shock of HB 3, and instead, they are most likely associated with the W3 complex. Additionally, Kilpatrick et al. (2016) made CO observations and suggested that the emission may be associated with the W3 star-forming complex, but not associated with the SNR HB 3. These prior observational results raise doubt as to whether the SNR HB 3 is truly interacting with dense molecular clouds. More encouraging, large CO maps (in the millimeter) toward the entire SNR of HB 3 from the Purple Mountain Observatory show broad CO lines from several positions (Zhou et al. 2016).

At the highest energy window, $\gamma$-ray emission from HB 3 was identified using previous missions of COS-B$^9$ (Strong 1977) and the Energetic Gamma Ray Experiment Telescope (Hartman et al. 1999); this was only possible because HB 3 has a large angular size (and hence fills the beam). Fermi $\gamma$-ray imaging shows that the $\gamma$-ray emission is spatially correlated with the SNR, originating from the interactions between particles accelerated in the SNR HB 3 and the decay of neutral pions produced in nucleon–nucleon interactions between accelerated hadrons and

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$^9$ https://www.cosmos.esa.int/web/cos-b

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![Figure 1. ROSAT PSPC X-ray image (0.3–2.4 keV) superposed on radio contours of HB 3 at 92 cm (520 MHz) from the Westerbork Northern Sky Survey (Landecker et al. 1987). All images have J2000 coordinates. The X-ray image has the intensity range of $(0.35–6.4) \times 10^{-3}$ counts s$^{-1}$ arcmin$^{-2}$. The image shows a center-filled X-ray morphology with an inner ring structure. The radio contours are 0.8, 4.9, 8.9, 13, and 17 mJy beam$^{-1}$.](image-url)
interstellar gas (Acero et al. 2016; Katagiri et al. 2016). Fermi and the High Energy Stereoscopic System observations show γ-ray emission in many SNRs, but not all (Acero et al. 2016). It has been suggested that J-type shocks may efficiently accelerate particles to emit γ-rays (Uchiyama et al. 2010). The total cosmic-ray spectrum injected into the Galaxy by an individual SNR is estimated by Celli et al. (2019).

In this paper, we present near-IR 2.12 μm narrow-band H$_2$ images along with broadband Spitzer Infrared Array Camera (IRAC) at 4.5 μm (IRAC-2) and WISE 4.6 μm (w2) images, which are interpreted mainly as H$_2$ emission dominated, and detections of broad-line CO emission in the millimeter window. They provide unambiguous evidence of interactions between HB 3 and molecular clouds, and reveal the large-scale structure of interacting sites. Section 3 shows a mosaic of ROSAT X-ray image, and Section 4 presents infrared images of near-IR H$_2$ imaging, together with Spitzer IRAC and WISE images. Section 5 describes detection of broad-line CO emission using the Heinrich Hertz Submillimeter Telescope (HHSMT or SMT) millimeter-wave and 12 m telescopes, and presents large-scale CO maps covering the southern shell of HB 3.

2. Observations

2.1. Spitzer GLIMPSE360

HB 3 is located in the Outer Galaxy at $l = 132.7^\circ$ and $b = 1.3^\circ$, one degree away from the Galactic plane. GLIMPSE360 (Whitney et al. 2011; ProgID = 60020) using the Spitzer warm mission (at 3.6 and 4.5 μm) observed the entire Perseus arm ($l = 90^\circ$–190°) at a distance of 2–4 kpc (see a large-scale gas by Alves et al. 2020), the Weak Outer Arm (all longitudes) at the distance from the Galactic center, $R_G \sim 12$–13 kpc, and the Far Outer Galaxy at $R_G > 16$ kpc. The survey shape followed the mid-plane of the CO/H$_1$ warp at $R_G = 13$ kpc. HB 3 was observed as part of GLIMPSE360, and the corresponding IRAC 3.6 μm (IRAC-1) and 4.5 μm (IRAC-2) images are shown in Figure 2. The IRAC observations used high-dynamic-range mode, with short (0.6 s) and long (12 s) frames at each position. The array was stepped nearly full-frame in the short direction and nearly 1/3-frame steps in the long direction, yielding a 3 times redundancy and effective exposure time of 32 s per point. In this manner we observed every spot in the survey area three times in quick succession. The observation dates of HB 3 observations are summarized in Table 1.

2.2. WISE Observations

WISE (Wright et al. 2010) is a whole sky mid-infrared (mid-IR) survey that uniquely provides data for heavily obscured SNRs located in the outer Galactic plane and also beyond Galactic plane. An example of WISE-detected SNR is HB 3, showing bright filamentary emission in Figures 3–5. Unique to the WISE observations and not covered by Spitzer (3.4 and 4.6 μm), it has a broadband filter centered at 12 μm (w3), and thus encapsulating the ubiquitous 11.3 μm PAH emission arising from the ISM and associated with SF activity. WISE w1 and w2 cover 3.4 and 4.6 μm, respectively, sensitive to stellar photospheric emission (continuum), and shock-excited lines, notably in w2. The WISE observations of HB 3 occurred in two passes on 2010, February 18 and August 22.
In order to improve the angular resolution of WISE, we applied high-resolution reconstruction to WISE-detected SNRs (Jarrett et al. 2012, 2013). The nominal spatial resolutions of WISE, ∼6″ at 3.4, 4.6, and 12 μm and 22 μm (Wright et al. 2010) are two times larger than those of Spitzer IRAC. The technique takes full advantage of the relatively stable and well-characterized point-spread function of WISE. For SNRs, this technique brings out the diffuse and filamentary emission distinguishing from point sources. Extragalactic examples are presented in Jarrett et al. (2013), demonstrating this technique dramatically improves the extraction of IR structure.

2.3. Near-IR Observations

We observed HB 3 on 2003 August 8 and 9 with the Widefield InfraRed Camera (WIRC; Wilson et al. 2003) on the Hale 200 inch (5 m) telescope at Mount Palomar. We took near-IR WIRC images (with each an FOV of 8.7″) toward the southern shell and southeastern shell, respectively (see Figures 6 and 7). The fields of view are marked in Figure 5 (as two white boxes). We observed a set of dithered positions (designed to uniformly cover the SNR), with a corresponding interleaved, dithered observations of an off position. A sky reference image was generated from the off images, and was subtracted from the on images after scaling to match the median sky brightness. This observation and analysis procedure preserved the diffuse emission of the SNR. In addition to the suite of near-IR filters, we imaged the SNR with a narrow-band filter centered on H$_2$ at 2.12 μm. The narrow-band filter widths are approximately 0.016 μm. The exposure time of H$_2$ is a combined 90 s from three back-to-back images of 30 s exposure (to reduce the number of saturated stars), with a total on-source integration time of 900 s for H$_2$. The sensitivity of the narrow-filter H$_2$ images are $1.7 \times 10^{-6}$ erg cm$^{-2}$ sr$^{-1}$ (∼1 data number).

The detailed data reduction methods are similar to those described in Rho et al. (2009); additionally, focal plane spatial distortion was derived from the images and corrected accordingly.

2.4. Millimeter Observations

We observed the $^{12}$CO $J = 3-2$ (CO(3-2), hereafter) line 345.7959 GHz toward a few select positions of the SNR HB 3 using the HHSMT (or SMT) located at Mt. Graham. The positions we observed were selected based on X-ray, radio, and previous CO observation to cover the east, south, and north parts of HB 3. The exact positions are summarized in Table 2 and the locations are marked in Figure 5. The observations took place 2003 May 17–19, and June 7–8, before the GLIMPSE and WISE observations were taken in 2010 as listed in Table 1 with the observed positions. We observed $^{12}$CO(2-1) (CO(2-1), hereafter) using the acousto-optic spectrometer (AOS) and filter-bank. The AOS spectra were measured with a 2048-channel, 1 GHz total bandwidth, an effective resolution of 1 MHz. The observations were made with three facility SIS mixer receivers placed at the Nasmyth focus. The beam efficiencies of single-polarization receivers in the frequency bands 210–275 GHz and 320–375 GHz are 0.77 for CO(2-1), and 0.48 for CO(3-2), respectively. The telescope beam size is 34″ at 217 GHz and 22″ at 347 GHz. A typical rms noise for CO(3-2) lines we observed is ∼0.17 K.

We also observed CO(2-1) at 230.53 GHz using the 12 m (12 m) telescope of the National Radio Astronomy Observatory at Kitt Peak on 1999 June 10. The beam size at 230 GHz was 27″. The beam efficiency at 230 GHz is 0.52.

2.5. X-Ray Observations of HB 3

HB 3 was observed using the X-ray telescope on ROSAT with the Position Sensitive Proportional Counter (PSPC), with exposure times $1.3 \times 10^3$ s. The background corrected counts rate is $2.69 \pm 0.05$ cts s$^{-1}$, which is comparable to IPC count rate 2.7 cts s$^{-1}$ (which is not background corrected). X-ray observations of HB 3 is based on the ROSAT PSPC analysis and initial results reported in the PhD thesis by Rho (1995). The remnant was covered using four pointing observations which pointed at the center, north, southeast, and southwest (sequence numbers are 500181n00, 500182n00, 500183n00 and 500184n00, respectively). The images have been mosaicked after exposure and background correction using software by Snowden et al. (1994), and is shown in Figure 1.

3. X-Ray Morphology of HB 3

Here we describe ROSAT imaging which provided the detailed X-ray morphology. Lazendic & Slane (2006) and Urošević et al. (2007) described ASCA observations which were combined with the ROSAT observations (see below). The mosaicked ROSAT PSPC image is shown in Figure 1. The PSPC image shows that the X-ray emission fills the interior, largely circular within the radio shell. The region size emitting its X-ray emission is somewhat smaller than what the radio emission shows; namely, no prominent shell that coincides with the radio shell. One noticeable structure is an X-ray ring inside the radio shell. The radius of the X-ray ring is 16′, while the radio shell has a much larger 42′ radius. And they are offset, the center of the X-ray ring is 10′ north of the center of the radio shell. A ring feature was resolved within the centrally concentrated emission. Excluding the extension to the north beyond the radio shell that is present in both the radio and X-ray, the remnant is circular with an 80′ diameter. The high-resolution 408 MHz radio continuum map (Landecker et al. 1987)
superposed on the X-ray contours is shown in Figure 1. A PSPC hardness map, corresponding to the ratio of a high energy (∼0.9–2.2 keV) band map to a low energy band map (∼0.5–0.9 keV) shows no spectral variation, indicating there is little variation of column density and temperature (Rho 1995; Rho & Petre 1998).
The X-ray spectral results yielded a line-of-sight absorption $N_H = 4.3(^{+0.25}_{-0.15}) \times 10^{21}$ cm$^{-2}$ and a temperature of $kT = 0.33 (^{+0.17}_{-0.14})$ keV (Rho & Petre 1998). Assuming HB 3 is in a Sedov phase, the X-ray temperature of $3.8(^{+2.0}_{-1.6}) \times 10^6$ K ($<0.33/0.0862 \times 10^6$ K) infers a shock velocity ($V_s$) of $522(^{+120}_{-120})$ km s$^{-1}$ ($V_s = 266.6 \times \sqrt{T_6}$ km s$^{-1}$ where $T_6$ is the temperature in the unit of $10^6$ K, see Winkler et al. 1974; Spitzer 1978). The angular size of HB 3 is $65^{\prime\prime} \times 100^{\prime\prime}$, which is equivalent to the radius of $18.5-29$ pc, which infers an age $(t)$ to be $1.8(^{+1.2}_{-0.6}) \times 10^4$ yr ($\sim 41.3 \times 10^4 R_{pc}/V_{km} s^{-1}$, where $R_{pc}$ is a radius in pc and $V_{km} s^{-1}$ is a shock velocity in km s$^{-1}$). The results are consistent with those using the ASCA spectra, which show Si lines at 1.86 keV (Lazendic & Slane 2006; Urošević et al. 2007), because the X-ray emission of HB 3 is dominated by soft X-ray emission. The mixed-morphology SNRs (Rho & Petre 1998) are in a transition phase between Sedov and radiative stages (Shelton et al. 1999) and show recombining plasmas (Yamaguchi et al. 2018, references therein). Thermal conduction and adiabatic expansion play important roles in the center-filled X-ray morphology (Zhang et al. 2019). The physical size of HB 3 is $45 \times 53$ pc, and the age of HB 3 is $(1.2-3.0) \times 10^4$ yr (see Section 3).

4. Infrared Emission

4.1. Mid-infrared Images Using Spitzer and WISE

The Spitzer IRAC 4.5 μm image of HB 3 exhibits thin filamentary structures, particularly bright at the eastern and southern shell structures, as shown in Figure 2. The filaments coincide with the radio emission of the SNR HB 3, indicating the filamentary emission belongs to HB 3 rather than the nearby W3 complex. The combined three-color images of IRAC 4.5 μm with IRAC 3.6 μm and WISE 12 μm images, Figure 2, reveals that the filamentary emission (in green) is distinct from the rest of infrared emission, and further confirms that the emission belongs to HB 3. The infrared colors from Spitzer images (at 3.6, 4.5, 5.8, and 8 μm) were studied by Reach et al. (2006) and the IRAC 4.5 μm emission (e.g., from SNRs that are interacting with molecular clouds) is shown to be from shocked H$_2$ emission originating from SNRs. We compare the IRAC-2 image with narrow-band H$_2$ images of HB 3, which strengthens that the emission is from H$_2$ emission (see Section 4.2 for details).

While the filamentary structures are associated with the SNR HB 3, there is another faint none-filamentary diffuse emission in the area of W3 complex near the southeastern part of the SNR HB 3 (see Figures 2 and 3). Two mechanisms have been invoked to account for the H$_2$ line emission: fluorescence induced by ultraviolet pumping (Black & van Dishoeck 1987; Le et al. 2017), and radiative cooling following collisional excitation by shock waves (Burton et al. 1989). The shocked H$_2$ characteristically have broad ($>20$ km s$^{-1}$) H$_2$ lines (e.g., see Reach et al. 2019), while the widths of fluorescent H$_2$ lines are expected to be considerably narrower. The shocked H$_2$ lines have rotational and vibrational excitation temperatures greater than $\sim 2000$ K for the H$_2$ lines (Burton et al. 1992). The faint diffuse emission in the 4.5 μm map may relate to the H II complex and have a mechanism from the absorption of UV photons or by resonance fluorescence of H$_2$ where the H$_2$ emission is a function of the UV flux (Shull & Beckwith 1982). The line strengths between 2-1 S(1) and 1-0 S(1) are used to distinguish between the two mechanisms. The ratio is $\sim 0.56$ for fluorescence of H$_2$ emission and 0.06–0.2 for shocked H$_2$ emission (Black & van Dishoeck 1987; Burton et al. 1989, 1992; Le et al. 2017). Basically the 1-0 S(1) 2.21 μm H$_2$ line is much stronger than the 2-1 S(1) 2.25 μm line for shocked gas. The faint diffuse emission may be due to fluorescence induced by ultraviolet pumping from the ionizing star of the H II region complex (Black & van Dishoeck 1987; Le et al. 2017). However, clumpy H$_2$-emitting structures among the diffuse emission are more likely to arise from shock heating since the ambient UV radiation probably does not penetrate the dense clumps. A classic example of shock heating in complex environments is the bright H$_2$ emission in the SNR IC 443 (Burton et al. 1988; Rho et al. 2001; Neufeld & Yuan 2008), which show clumpy and knotty structures and a relatively weak UV radiation field. Spectroscopic follow-up observations would be required to unambiguously distinguish the two different mechanisms of H$_2$ emission.

Our 2-degree high-resolution reconstructed WISE mosaic covers the entire SNR and nearby W3 complex, Figure 3, revealing additional extended H$_2$ emission associated with HB 3. The w2 emission at 4.6 μm exhibits a morphology that is nearly identical to that of Spitzer IRAC-2 image, which is to be expected because the bands are very similar, encapsulating the H$_2$ emission line, and the enhanced resolution of WISE is comparable to the beam of IRAC. The 2-degree mosaic reveals a large scale of interaction site between the SNR HB 3 and local dense gas from molecular clouds. The WISE and Spitzer imaging distinguish between the different interaction sites, notably the boundary with the W3 complex to the east. The H$_2$ emission traces thin filamentary structures, particularly bright emission at the southern and eastern shell. In more detail, this shock-excited emission has a distinctive shape of a “butterfly”
(or “W”), which is clearly the interacting sites between the SNR HB 3 and nearby molecular clouds. Interestingly, it is not just the dense gas of W3 complex, but the interaction zone in the southeast appears to be between HB 3 and the H II regions of the W3 complex.

The mid-IR imaging highlight the H$_2$ emission at the boundary between the SNR and a nearby HII region of the W3 complex. The northeastern filament, central, (bright) eastern and southern shell areas are de-marked in Figure 5, and the positions of bright H$_2$ are summarized in Table 3. About half of the SNR HB 3 emits H$_2$ emission from east to south, and the emitting area shows a shape of a butterfly (similar to a rotated letter “W”) in projection as shown in Figure 3. As noted earlier, this H$_2$ emitting region indicates the interaction between the SNR HB 3 and nearby molecular clouds. The other half of HB 3 to the north and west shows no H$_2$ emission, likely because there are no dense gas clouds, or the density of the medium is relatively low overall and rovibrational H$_2$ emission is too faint to detect. Figure 4 shows WISE 4.6 μm map superposred on AKARI 160 μm cold dust map. The correlation between 4.6 μm filaments and cold dust map indicates that WISE 4.6 μm emission is shocked H$_2$ gas from interacting with cold and dense clouds. More importantly, the 4.6 μm filaments are located along the radio shell of HB 3 shown in Figure 1, indicating the emission is related to the SN shocks.

We provide a finding chart, Figure 5, of the locations of the IR emission. The eastern filaments, Figures 2 and 3, have very sharp edges, which appear within the box marked as “East” in Figure 5. Along the Southern shell we see two branches of filaments: one is the outer southern shell and the other is the inner southern shell, marked as “South-out” and “South-in,” respectively. The locations of the IR emission associated with the SNR and the FOVs of the H$_2$ and millimeter CO observations will be discussed in Sections 4.2 and 5, respectively. We provide a finding chart, Figure 5, of the locations of the IR emission, and the FOVs of the H$_2$ (in Section 4.2) and millimeter CO observations (see Section 5).

The range in morphology is likely due to geometric viewing effects. Similar to the Cygnus Loop (G74.0-8.5 Hester et al. 1994), the mid-IR mosaic of HB 3 shows a network of filaments. For example, the brightest H$_2$ emission of HB 3 exhibits very smooth filamentary emission, as if it is from a gently rippled sheet as demonstrated by Hester et al. (1994) in the Cygnus Loop. The bright emission of the eastern filaments are likely viewed edge-on (in tangential direction relative to the shock). The smoothness of the emission indicates that the preshock medium is homogeneous. This morphology of H$_2$ emission in HB 3 is in stark contrast to the knotty H$_2$ structures seen in IC 443. From early work in 1980s and 1990s, IC 443 became the prototype mixed-morphology SNR, revealed with near-IR narrow-filter H$_2$ imaging (Burton et al. 1988; Richter et al. 1995) and Two Micron All Sky Survey (2MASS) broadband imaging (Rho et al. 2003). Another prominent Galactic SNR is W44, which also shows mostly knotty structures of H$_2$ emission, although faint smooth filamentary structures are also seen (Reach et al. 2005, 2006). The H$_2$ knotty emission is much brighter than that of whispy filamentary structures for many cases in IC 443 and W44. On the other hand, the southern H$_2$ emission in HB 3 is remarkably similar to the southern part of H$_2$ emission in W44. We note that HB 3 is special because the remnant shows not only interactions with molecular clouds but also interactions.
The mid-IR Spitzer IRAC-2 and WISE w2 images reveal that the SNR HB 3 is interacting with the W3 H II complex. The shocked H$_2$ emission appears at the boundary between them and has a filamentary morphology with clumpy and compressed structures at some locations, indicating shocks. The nature of the shock is still to be determined. They may be from C- or J-shocks, with compression tempered by the underlying magnetic field. Follow-up infrared spectroscopy to detect rotational and vibrational H$_2$ lines will help to distinguish the nature of the shock as it was done for other SNRs which are interacting with clouds (Hewitt et al. 2008) and G357.7+0.3 (Rho et al. 2017).

In summary, the molecular H$_2$ imaging impressively reveals the boundaries between the SNR HB 3 and the H II region of the W3 complex, as well as the shocked SN shell itself.

### 4.2. Near-infrared Palomar WIRC Imaging

We show that the morphology of the Spitzer IRAC-2 and WISE w2 emission is identical to that in narrow-band H$_2$ imaging as shown in Figures 6 and 7. The WIRC narrow-band H$_2$ 2.12 $\mu$m images cover parts of the south and southeast regions. The exact regions observed with WIRC are marked in Figure 5. The Spitzer IRAC images have a 2.5″ spatial resolution, while the Palomar WIRC images have a seeing limited spatial resolution with a PSF of 0.6″. Figures 6 and 7 show that the WIRC narrow-filter H$_2$ images are almost identical to those of 4.5 $\mu$m Spitzer images, revealing very thin filamentary structures, to the resolution limit of our Palomar WIRC imaging (1″ = 0.0095 pc in HB 3). This demonstrates that 4.5 $\mu$m Spitzer imaging traces H$_2$ emission, as, for example, it has been demonstrated in the case of W44 (Reach et al. 2006).

Figure 7 shows filaments from the southeast of HB 3 and at the bottom right corner of the image shows H$_2$ emission with clumpy or knotty structures. The knotty H$_2$ structures are shown in the zoomed panel in Figure 7(d). This region is where the SNR interacts with the W3 complex, but H$_2$ emission still shows nice shell structures. The spatially high-resolution H$_2$ imaging with WIRC further confirms that the emission of Spitzer IRAC-2 and WISE w2 originates from shocked H$_2$ emission from interaction of the SNR HB 3 with dense molecular gas.

### 4.3. H$_2$ Line Contribution to Mid-infrared Images

We measured the fluxes at a few bright peaks in the Spitzer images (for $3 \times 3$ pixels with a 1.2″ pixel size) and averaged the fluxes in the WIRC H$_2$ images for the same area. We selected small areas which do not include any stars. Table 4 summarizes the fluxes of the narrow-band H$_2$ (2.12 $\mu$m) and Spitzer images at 3.6 and 4.5 $\mu$m. The filaments in WIRC H$_2$ image show that they are thinner than Spitzer resolution of 3″, but the measurements for smaller areas introduce large errors. The WIRC narrow-band 2.12 $\mu$m fluxes (erg per second per steradian) is converted to mega-jansky per steradian after accounting for the filter transmission curve. The background emission at these short wavelengths is low and it is near-zero measured from the lowest emission in the images. The archival Spitzer images are zodi-subtracted. The observed ratios of IRAC-2/H$_2$ (2.12 $\mu$m) and IRAC-2/IRAC-1 are 0.8–1.2 and 0.9–1.9, respectively. The filament A shows brighter than other $B-E$ filaments and shows higher ratios of IRAC-2/H$_2$ and IRAC-2/IRAC-1 than others. The filament A appears the combination of multiple filaments, as shown in the bright emission (Figure 7(d)). Other filaments

with the W3 H II region complex. A few SNRs have nearby H II regions, for example W44 and W28 (Rho et al. 1994; Reach et al. 2005), but the H II regions are in projection in the line of sight, and there has not been any cases in which direct interaction with H II regions has been conclusively demonstrated. HB 3 is therefore a very interesting mix-morphology SNR case.
(B − E) are isolated thin filaments. Reach et al. (2006) show that the IRAC-2/IRAC-1 ratios of another 10 molecular interacting SNRs range from 1−3 (Reach et al. 2006).

Reach et al. (2006) suggest that the IRAC emission is largely H$_2$ lines in IRAC-1 and IRAC-2 bands from H$_2$. IRAC-1 is composed of O(5) and S(13) H$_2$ lines, and the IRAC-2 is composed of S(11) and S(9) H$_2$ lines and possibly from CO emission. Neufeld & Yuan (2008) examine the IRAC maps of the supernova remnant IC 443 and suggest that the IRAC-1 and IRAC-2 are dominated by H$_2$ v = 1 − 0 O(5) and v = 0 − 0 S(9) based on modeling of the H$_2$ excitation, and CO vibrational emissions do not contribute significantly to the observed IRAC-2 intensity since CO requires very high densities (>10$^{10.8}$ cm$^{-3}$). AKARI IRC spectra cover the wavelengths of IRAC-1 and IRAC-2 bands, and Shinn et al. (2011) detected H$_2$ lines from IC 443. The IRC-detected H$_2$ lines within the IRAC-1 band are 1−0 O(5) at 3.23 μm, 0−0 S(15) at 3.62 μm, 1−0 O(7) at 3.81 μm, and 0−0 S(13) at 3.84 μm, and the lines in the IRAC-2 are 0−0 S(11) at 4.18 μm 0−0 S(10) at 4.41 μm 1−0 O(9) at 4.58 μm, and 0−0 S(9) at 4.69 μm. Neufeld & Yuan (2008) suggest that the relative strengths of IRAC band emission are consistent with pure H$_2$ emission from shocked material with a power-law distribution of gas temperatures. The IRAC-2/IRAC-1 ratios depend on the density (Neufeld & Yuan 2008; Shinn et al. 2011, 2012) as well as the slope of the temperature distribution.

In summary, Spitzer IRAC images at 3.6 and 4.5 μm can be explained by bright lines of molecular hydrogen for the shocked filaments and would not require a contribution from the continuum. Future sensitive spectroscopic follow-up
such as using the James Webb Space Telescope (JWST) to study the shock properties and astrochemistry to form high-energy emission lines. Observations for IRAC-1 and IRAC-2 (from 3.2 μm to 5 μm) were used, along with the James Webb Space Telescope (JWST), to detect faint H₂ lines and test how the parameters of H₂ excitation differ in HB 3, densities, or temperature distribution compared to other regions. The representative, resolved spectra are shown in Figure 8, and the grid maps are shown in Figures 9 and 10. A spectrum with the broadest line from the GRID map of each region was fit using two component Gaussian profiles with wide and narrow lines; the fit results are summarized in Table 5.

When we compare the CO GRID map and H₂ emission as shown in Figures 9 and 10, it is clear the interaction between HB 3 and dense molecular clouds based on the detections of broad CO(3-2), CO(2-1), and 13CO(2-1) molecular lines from a few positions (S1, S2, B1, B2, and B3) of HB 3 along the H₂ emitting region. The Kitt Peak CO(1-0) line toward position B1 is shown in Figure 11. The broad lines show line widths of 7–21 km s⁻¹. The detection of such broad lines is unambiguous, dynamic evidence showing that the SNR HB 3 is interacting with dense gas. Such broad CO lines require the FWHM to be greater than 6 km s⁻¹ (Kilpatrick et al. 2016) for kinematic (shock) broadening. The CO broad lines are detected from two branches of the southern shell where H₂ emission is detected and prominent. Whereas in contrast, CO emission toward the H II region of W3 complex detects only a width of 3 km s⁻¹ which indicates that the SN shock did not propagate into the eastern H II region.

Figure 12 shows the kinematic distribution between the LSR velocity and the FWHM width shown in Table 5. The 3-H II regions have a systematic velocity of ~41 km s⁻¹. The narrow components of both H II regions and the SNR HB 3 are at a velocity of ~41 to ~46 km s⁻¹. The broad lines along the southern shell of HB 3 appear at velocities of ~32 to ~39 km s⁻¹, and the boundary regions between HB 3 and the H II region are at velocities of ~40 and ~47 km s⁻¹, which probably include the material moving toward us and receding from us. The CO clouds toward the position of B3 are at a velocity of ~31 km s⁻¹, which is gas that is mainly receding from us (it is redshifted relative to ~45 km s⁻¹).

### 5. Millimeter and Submillimeter CO Emission

#### 5.1. Broad CO Spectra

Figure 5 shows six regions that we observed CO(3-2), CO (2-1), and 13CO(2-1) lines using HHSMT. These positions were selected based on radio and X-ray images before the Spitzer and WISE images were available. The southern (S) positions are along the southern shell and the boundary (B) positions are close to the boundaries between the SNR HB 3 in the southeastern direction and the H II regions of W3 complex. The regions of S1, S2, B1, B2, and B3 in Figure 5, show broad molecular lines (BMLs) in CO(2-1). The representative, resolved spectra are shown in Figure 8, and the grid maps are shown in Figures 9 and 10. A spectrum with the broadest line from the GRID map of each region was fit using two component Gaussian profiles with wide and narrow lines; the fit results are summarized in Table 5.

When we compare the CO GRID map and H₂ emission as shown in Figures 9 and 10, it is clear the interaction between HB 3 and dense molecular clouds based on the detections of broad CO(3-2), CO (2-1) and 13CO(2-1) molecular lines from a few positions (S1, S2, B1, B2, and B3) of HB 3 along the H₂ emitting region. The Kitt Peak CO(1-0) line toward position B1 is shown in Figure 11. The broad lines show line widths of 7–21 km s⁻¹. The detection of such broad lines is unambiguous, dynamic evidence showing that the SNR HB 3 is interacting with dense gas. Such broad CO lines require the FWHM to be greater than 6 km s⁻¹ (Kilpatrick et al. 2016) for kinematic (shock) broadening. The CO broad lines are detected from two branches of the southern shell where H₂ emission is detected and prominent. Whereas in contrast, CO emission toward the H II region of W3 complex detects only a width of 3 km s⁻¹ which indicates that the SN shock did not propagate into the eastern H II region.

### 5.2. CO Broad Lines and CO Maps in the Southern Shell

The CO broad lines are located at the lower part of the S1 region where there is brighter H₂ emission as well, similar to the central regions. An isolated, thin H₂ filament in the northern part of S2 shows CO broad lines with a relatively small, FWHM 7.4 km s⁻¹, which may imply that this isolated shock is spatially resolved. The broader lines of 15–20 km s⁻¹ may be due to a shock velocity of the same order, but alternatively for some cases, the lines could be multiple shocks of smaller broad lines, closer to ~8 km s⁻¹. Further follow-up observations with a higher spatial resolution may be needed to distinguish between the two components. Zhou et al. (2016) have presented broad CO lines from the southeastern part of HB 3 and suggested shock-cloud interaction in HB 3. Since the CO line profiles (Zhou et al. 2016) differ from the ones presented in this paper, they may cover somewhat different area, but their position C seems to be from the eastern shell, where there is bright H₂ emission. One-to-one correspondence between shocked H₂ emission and broad CO lines are suggested from faint H₂ emission in IC 443 (Rho et al. 2001). Thus, we can expect this correlation for the shocked H₂ gas, which appears along with the radio shell of HB 3.

| Table 2 |
|---|---|---|
| **Observed Millimeter HHSMT and Near-infrared WIRC Positions of HB 3** |
| **Position** | **R.A., Decl. (J2000)** | **Area (spacing)** |
| **S1 (PEAK1)** | 02:21:56.10, +62:04:59.0 | 180° × 180° (60°) |
| **S2 (PEAK4)** | 02:17:37.75, +61:51:49.5 | 180° × 180° (60°) |
| **B1 (M3, PEAK2)** | 02:20:22.56, +62:07:32.8 | 180° × 180° (60°) |
| **B2 (M2, HV)** | 02:19:59.95, +62:06:45.7 | 180° × 180° (60°) |
| **B3 (M1, PEAK3)** | 02:19:09.86, +62:10:25.7 | 30° × 30° (10°) |
| **SE (EQ)** | 02:21:55.41, +61:58:40.9 | 420° × 420° (60°) |
| **EI (E1)** | 02:22:18.15, +62:48:40.0 | 360° × 300° (60°) |

| **WIRC** | **Near-IR Observations** |
| **WIRC1** | 2:19:59.636, +62:06:39.07 | 9° × 9° |
| **WIRC2** | 2:17:46.742, +61:52:34.08 | 9° × 9° |

**Note.**

*a* The name, “S” indicates the southern shell, and “B” shows “Boundary” between the SNR HB 3 and H II region of the W3 star-forming complex. “SE” is the SE position of HB 3. The name in parenthesis is the original name in the HHSMT data.

| Table 3 |
|---|---|---|
| **Bright H₂ Filaments in HB 3** |
| **Regions** | **R.A., Decl. (J2000)** | **Area (°)** |
| **Eastern Shell Filament (East)** | 2:23:05.03, +62:33:01.56 | 12 × 31 |
| **Southern Inner Shell (South-In)** | 2:23:05.70, +62:36:09.57 | ... |
| **Southern Outer Shell (South-Out)** | 2:13:52.68, +62:04:51.16 | 44 × 12 |
| **SE Boundary with W3 complex** | 2:14:48.98, +62:06:16.58 | ... |
| **Central H₂ position (Center)** | 2:18:57.72, +61:47:53.34 | 31 × 9 |
| **NE shell (NEShell-H₂)** | 2:22:18.15, +62:48:40.0 | 9° × 9° |

**Notes.**

*a* Brightest H₂ position for eastern shell, southern shell 1 and 2, and SE boundary region, respectively (see Figure 5).

*b* A small portion of the northeastern shell appears in green (top left) in Figure 3.

As an example, the name “S” indicates the southern shell, and “B” shows “Boundary” between the SNR HB 3 and H II region of the W3 star-forming complex. “SE” is the SE position of HB 3. The name in parenthesis is the original name in the HHSMT data.
5.3. Large-scale CO Maps and Comparison with H$_2$ Gas

Figure 13 shows CO(2-1) maps with velocity channel maps, compared with the Spitzer H$_2$ map. The upper H$_2$ filament (in the yellow box of Figure 13 marked as the southern outer shell in Figure 5) matches very well to the $-35$ km s$^{-1}$ (or $-41$ km s$^{-1}$) cloud. It indicates the H$_2$ emission is shocked gas due to the interaction of the SNR HB 3 and cold molecular clouds. The velocity at $-35$ km s$^{-1}$ is the same velocity range observed toward S1 and S2 clouds in the CO(3-2) HHSMT spectra as shown in Figures 12 and 9. Zhou et al. (2016) concluded that the remnant is located at the nearside of the molecular cloud because redshifted CO wings are observed. We find the CO clouds of the southern shell (S1 and S2) and central regions (B3) are at velocities $-30$ to $-36$ km s$^{-1}$ and the velocity channel map at $-35$ km s$^{-1}$ also infers a similar range. The shocks in Regions B1–B3 and Regions S1–S2 are progressing in somewhat different directions, generally on the front and far side of the SNR.

5.4. CO Line Profiles at the Boundary Between HB 3 and the W3 Complex

Figure 10 shows a CO(2-1) spectrum toward the SE direction of HB 3 where it is in the H II region; the area is marked in Figure 5. The CO line shows two narrow components (see Table 5). We covered a large area of $3.5' \times 3.5'$ toward this direction, and no broad CO line is detected. From the mid-IR WISE and GLIMPSE maps, the position is clearly located in the nearby W3 complex. Hence, the CO spectra are indicative of the H II region. The line widths are about $3-4$ km s$^{-1}$. WISE and GLIMPSE imaging do not show any shocked molecular hydrogen emission from this area, indicating that the SNR boundary is further northwest of the H II region. H$_2$ emitting regions follow the boundary of the SNR HB 3. We also observed an eastern position (EI; the inner part of the eastern shell), but inside the bright eastern H$_2$ filaments, as shown in Figure 5 that covers $8' \times 5'$, and no CO line is detected toward this position. Moreover, this area coincides with no H$_2$ emission in both Spitzer IRAC-2 and WISE w2 images; see Figure 2 or 3.

The spacing of our CO GRID spectra toward the B3 region in Figure 10 is 10", and the spectra show the broadest CO lines. Their H$_2$ emission morphology is knotty and clumpy as shown in Figures 2 and 5. They are either gas that is moving toward and away from us (i.e., less material in tangential), which causes broader CO lines; or more likely, the emission is due to C-shock origin with a higher preshock density. The B1 region has both filamentary and knotty H$_2$ emission as shown in Figure 10.

The B2 region exhibits the most complicated CO line profiles, as shown in Figure 10. The velocities vary considerably within the 180$''$ x 180$''$ area. It is likely the clouds are interacting with both the SNR and the H II region. In contrast, the velocities of the line profiles of the B3 region remain the same, but the strengths of the WISE mid-IR components significantly vary across the area.

6. Star-forming Activity and Young Stellar Objects (YSOs)

We identify star-forming activities in and near HB 3 and W3 complex by investigating the distribution of Class I and II YSOs using two color–color diagrams from the 2MASS (Skrutskie et al. 2006) and WISE point-source catalogs. We adopt the YSO criteria described in Koenig & Leisawitz (2014, hereafter KL14) as in Zhou et al. (2016). The source classifying algorithm (KL14) first defines the SFGs (Jarrett et al. 2019) and asymptotic giant branches (AGBs) under their specific criteria in color–color diagrams (Equations (5)–(8) and 9–(11) in KL14 for SFGs and AGBs, respectively). They then select Class I and II YSOs with WISE color–color diagram. The criteria for Class I YSOs with WISE data only are $w2 - w3 > 2$ and $w1 - w2 > 0.42 \times (w2 - w3) + 2.2$ and $w1 - w2 > 0.46 \times (w2 - w3) - 0.9$ and $w2 - w3 < 4.5$. For Class II YSOs, the criteria are the following: $w1 - w2 > 0.25$ and $w1 - w2 < 0.9 \times (w2 - w3) - 0.25$ and $w1 - w2 > 1.5 \times (w2 - w3) + 2.1$ and $w1 - w2 > 0.46 \times (w2 - w3) - 0.9$ and $w2 - w3 < 4.5$. The locations of Class I and II YSOs are marked on the WISE color–color diagram in Figure 14(a). The remaining sources are investigated again with the photometry measurement of 2MASS and WISE so that the criteria of Class II YSOs are $H - K_s > 0.0$, $H - K_s > -1.76 \times (w1 - w2) + 0.9$, $H - K_s < (0.55/0.16) \times (w1 - w2) - 0.85$, and $w1 \leq 13.0$. In order to determine Class I YSOs, we add a criterion $H - K_s > -1.76 \times (w1 - w2) + 2.55$. The locations of Class I and II YSOs are marked on the 2MASS and WISE color–color diagram in Figure 14(b).

Figure 15(a) shows SF activities (marked as Regions A–F) around the SNR HB 3. Figure 15(a) shows the locations of all Class I and II YSOs in the inspected field on the WISE three-color map. The distribution of YSOs shows that some of YSOs are in the infrared dark clouds. There are three types of SF activities; (i) in the dark clouds near W3 complex and SNR with the examples of Regions C and D; (ii) at the boundary between HB 3 and W3 H II region complex along the W shape of H$_2$ emitting area, with the examples of Regions A and B; and (iii) at the H$_2$ emitting arc structures of SN southern shell showed by YSOs between the southern inner and outer shell (see Figure 5), with examples of Regions E and F. Figure 15(b) shows the locations of YSOs marked on the AKARI 160$\mu$m image. Class I YSOs are located along the long filaments or
structures. The shock wave of HB 3 may have plowed through YSOs and located them at the southern shell of the SNR. Recent studies show that the relatively older YSO populations have a higher spatial difference to the birthplace (Elmegreen 2018) or the higher kinematic difference from the dense molecular clouds (Lim et al. 2021). The HB 3 regions also have been assumed to experience the repeated powerful feedback from the massive progenitor of HB 3 (e.g., Zhou et al. 2016). Such events could result in a more reduced spatial and kinematic correlation between the Class II YSOs and mother clouds. Moreover, since Class I YSOs are associated with dense molecular clouds, it would be harder for the blast wave to plow the dense gas, and instead, the shock wave would slow down where we observe both Class I and II YSOs at the boundary regions between HB 3 and W3 Complex. One needs to bear in mind that the comparison of separate evolutionary tracers of such SF activities, e.g., virial parameter ($\alpha_{\text{vir}}$) versus luminosity—mass ratio ($L/M$; Lim & De Buizer 2019) or unambiguous identification of YSOs with follow-up spectroscopy is still needed to support our conclusion.

7. Physical Conditions of Shocked Gas in HB 3

7.1. Resolved Shock Structures in H$_2$ and CO

The H$_2$ emission of HB 3 exhibits largely thin filamentary structures and knotty structures. The thickness is 1 or 2 WIRC pixels (one pixel size is 0.25″), which is comparable to 0.8−1.6 x 10^{-16} cm for the distance of HB 3. The filamentary H$_2$ emission is unlikely to arise from very dense cores ($n_0 > 10^4$ cm$^{-3}$), because the filaments are coherent and long (> a few parsecs), as discussed in Reach et al. (2005). The filamentary structures require that the preshock medium be very uniform and probably relatively low ($<10^3$ cm$^{-3}$; see the application of shock models in the next section) gas density. We compare H$_2$ emission with shock models. The H$_2$ brightness of 0.6−2 x 10^{-5} erg s$^{-1}$ cm$^{-2}$ sr$^{-1}$ is consistent with a J-shock with a low density of $n_0 = 10^3$ cm$^{-3}$ (Hollenbach & McKee 1989). Knotty structures are more than a factor of 3 brighter than those of filamentary H$_2$ emission; see Figure 7(d). It is likely that the shocks are moving along the line of sight, or they are from multiple shocks including the shocks moving in the light of sight.

The primary narrow component is at a velocity of 42 km s$^{-1}$ and is likely pre-shocked gas. The $V_{\text{lsr}}$ of broad CO lines range from −30 and −46 km s$^{-1}$, which is a large velocity difference, as shown in Table 5. In the GRID maps, we see the broad-line structures change within 3 × 3 maps.

The CO observations of HB 3 is previous presented by Kilpatrick et al. (2016), the authors observed the BML region toward HB 3 and the W3(OH) HII region. Kilpatrick et al. (2016) concluded that the broad lines are not associated with the SNR. Our first CO data were observed before the infrared H$_2$ images were available. However, when the mid-IR GLIMPSE and WISE data are factored into this analysis, it is then clear that the H$_2$ emission reveals the regions where the SNR HB 3 is clearly interacting with the molecular clouds, and the regions where the SNR HB 3 is interacting with the H II region of W3. The broad CO lines are associated with the H$_2$ radiative cooling lines at the shock front, as shown in Figures 9–11. Our observations show a strong correlation between H$_2$ and broad CO lines, not unlike the case of the SNR IC 443 where one-to-one correspondence between H$_2$ and broad CO are reported (Rho et al. 2001). The shock-excited molecular hydrogen traces
where the gas has been heated, kinematically broadening the observed CO emission lines. The fact that the SNR HB 3 is interacting with nearby molecular clouds suggests that the progenitor of HB 3 is born or associated with a GMC. However, the progenitor must be later than B0 (Rho et al. 1994) in order to have direct interaction between the SNR and local molecular clouds, because more massive stars would have strong winds, of which wind-driven bubbles clear away the clouds.

The SNR HB 3 shows very unique and interesting CO structures. First, the velocity of LSR significantly varies across the field, as shown in Table 5, and Figure 12. Second, the broad lines appear and disappear on small physical scales: Figure 10 shows at 10\textarcmin scales, the broad lines appear and disappear. Third, the H2 imaging indicates that individual shocks are resolved, where the FWHM of CO line is small, 7 km s\(^{-1}\) at a few positions in HB 3.

### 7.2. Applications of Shock Models to HB 3 Spectra

In this section, we model the line profile of the CO(3-2) transition and interpret what is observed. The intensity of the CO(3-2) transition along the line of sight \(s\) is obtained by solving the radiative transfer

\[
\frac{dI_r(s, \theta)}{ds} = \epsilon_r(s, \theta) - \kappa_r(s, \theta)I_r(s, \theta),
\]

where \(\epsilon\) and \(\kappa\) are, respectively, the emissivity and absorption coefficient, and defined as

\[
\epsilon_r(s, \theta) = \frac{\hbar \nu_{32}}{4\pi} n_3(s) A_{32} \phi_s(T_{\text{gas}}(s), \theta),
\]

\[
\kappa_r(s, \theta) = \frac{\hbar \nu_{32}}{4\pi} [n_2(s) B_{23} - n_3(s) B_{32}] \phi_s(T_{\text{gas}}(s), \theta),
\]

where \(\nu_{32}\) is the frequency of the CO(3-2) transition, \(n_2\) and \(n_3\) are the populations of the lower \((J = 2)\) and upper \((J = 3)\) excited stages of this transition, \(A_{32}, B_{32}\) and \(B_{23}\) are the Einstein coefficients of the spontaneous, stimulated emissions and absorption, respectively. \(\phi_s(\theta)\) is thermal broadening of the line, which is a function of the viewing angle \(\theta\) (i.e., the angle between the shock velocity and the line of sight). To obtain the line profile, we transform the argument \(\nu\) into the velocity \(v_r\) \((\phi_v \sim \phi(v_r))\), which is

\[
\phi(v_r) = \frac{\lambda_{32}}{\sqrt{2\pi} \sigma} \exp \left[ -\frac{(v_{\text{obs}} \cos \theta - v_r)^2}{2\sigma^2} \right],
\]

where \(\lambda_{32}\) is the wavelength of the CO(3-2) transition, \(\sigma \sim T_{\text{gas}}^{0.5}\) is the gas thermal dispersion velocity, and \(v_{\text{obs}} = v_{\text{gas}}(z) - v_{\text{shock}}\) is the shock velocity in the observer frame with \(v_{\text{gas}}(z)\) the gas velocity at position \(z\) in shock frame and \(v_{\text{shock}}\) the shock velocity. If the ambient gas motions with a velocity of \(v_{\text{pre-shock}}\), we take it into account to correct the velocity in the observer frame as \(v_{\text{obs}} \cos \theta + v_{\text{pre-shock}}\). The velocity \(v_{\text{gas}}(z)\) and temperature \(T_{\text{gas}}(z)\) of the shocked gas in the shock frame are calculated in a 1D plane-parallel Paris–Durham shock model (Lesaffre et al. 2013; Flower & Pineau des Forêts 2015; Godard et al. 2019; Lehmann et al. 2020). We use nonstationary C-shocks that have dynamical ages shorter than the time required for a C-shock to reach the steady state, which is composed of a C-shock and a J-shock tail (referred as CJ-shocks). Note that in the case of a
plane-parallel approximation, \( s = z / \cos(\theta) \), with \( z \) post-shock position. Then, the emissivity \( \epsilon \) and the absorption coefficients \( \kappa \) are estimated by the large velocity gradient assumption (Sobolev 1960; Surdej 1978).

Figure 16 shows the best match of the CO(3-2) profile predicted from the shock model as compared to observations toward three positions: S1 (top panel), S2 (middle panel), and B1 (bottom panel). The best parameters from the model are listed in Table 6. The inferred shock velocity is 20–40 km s\(^{-1}\), a density \( 6 \times 10^3 - 2 \times 10^4 \) cm\(^{-3}\), and the magnetic field is \( >200 \) \( \mu \)G, which is more than one order of magnitude larger than 20 \( \mu \)G measured by radio observations toward this direction (Gray et al. 1999). Gray et al. (1999) estimate the magnetic field strength of 20 \( \mu \)G in average toward the W3/W4/W5/HB 3 complexes over 40° of sky area, where much of the emission is associated with relatively diffuse, ionized gas surrounding the complex. For the regions with dense-shock tracers in HB 3, we find the interaction is with the actual molecular cloud as opposed to the diffuse halo of the complex. For that reason, the 20 \( \mu \)G represents a lower bound for the magnetic field strength of HB 3. It is undoubtedly much greater in the dense regions.

The magnetic field, inferred from diffuse through molecular cloud Zeeman splitting, is \( B = 0.5 \times n^{0.65} \) \( \mu \)G where \( n \) is a density. For a density of \( 10^4 \) cm\(^{-3}\), \( B \approx 200 \) (80–500) \( \mu \)G (see Figure 1 of Crutcher et al. 2010). Our estimated strength of the magnetic field of \( >200 \) \( \mu \)G does not contradict those in Crutcher et al. (2010).
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Table 5
Summary of CO Line Properties

| Position | Line   | Frequency | Offset | Component | $V_{\text{lsr}}$ | FWHM     | $\int T_d v$ | ms      | $\tau_{\text{rot}}$ (minutes) | Figures |
|----------|--------|-----------|--------|-----------|-----------------|----------|--------------|--------|-------------------------------|---------|
| S2       | CO(3-2)| 345.7959  | (0,0)  | 1         | $-32.48 \pm 0.16$ | 7.35 $\pm 0.41$ | 11.16 $\pm 0.48$ | 0.17 | 5                              | 8, 9    |
|          |        |           |        | 2         | $-41.67 \pm 0.04$ | 2.55 $\pm 0.14$ | 7.26 $\pm 0.31$ |        |                               |         |
| S1       | CO(3-2)| 345.7959  | (0, -60) | 1         | $-38.09 \pm 0.26$ | 15.34 $\pm 0.61$ | 24.32 $\pm 0.83$ | 0.14 | 5                              | 9       |
|          |        |           |        | 2         | $-53.80 \pm 0.22$ | 3.98 $\pm 0.56$ | 3.63 $\pm 0.46$ |        |                               |         |
| B3       | CO(3-2)| 345.7959  | (10, -10) | 1         | $-30.91 \pm 0.15$ | 20.17 $\pm 0.36$ | 47.76 $\pm 0.60$ | 0.12 | 6                              | 8, 10   |
|          |        |           |        | 2         | $-44.73 \pm 0.03$ | 2.25 $\pm 0.08$ | 6.79 $\pm 0.23$ |        |                               |         |
| B2       | CO(3-2)| 345.7959  | (0, +60) | 1         | $-41.18 \pm 0.15$ | 16.38 $\pm 0.35$ | 43.74 $\pm 0.78$ | 0.18 | 5                              | 8, 10   |
|          |        |           |        | 2         | $-43.89 \pm 0.08$ | 1.73 $\pm 0.05$ | 2.75 $\pm 0.25$ |        |                               |         |
| B1       | CO(3-2)| 345.7959  | (0, -60) | 1         | $-39.94 \pm 0.37$ | 15.88 $\pm 0.82$ | 19.87 $\pm 0.95$ | 0.21 | 6                              | 10      |
|          |        |           |        | 2         | $-43.36 \pm 0.03$ | 2.24 $\pm 0.06$ | 13.35 $\pm 0.41$ |        |                               |         |
| B1       | CO(3-2)| 345.7959  | (0, 0)  | 1         | $-47.68 \pm 0.16$ | 17.73 $\pm 0.27$ | 43.08 $\pm 0.70$ | 0.16 | 5                              |         |
|          |        |           |        | 2         | $-43.17 \pm 0.06$ | 1.92 $\pm 0.13$ | 4.94 $\pm 0.31$ |        |                               |         |
| B1       | CO(2-1)| 230.5379  | (+10, +20) | 1         | $-46.58 \pm 0.03$ | 17.80 $\pm 0.03$ | 23.18 $\pm 0.02$ | 0.06 | 53                             | 11      |
|          |        |           |        | 2         | $-43.96 \pm 0.03$ | 1.87 $\pm 0.03$ | 5.32 $\pm 0.02$ |        |                               |         |
|          |        |           |        | 3         | $-40.86 \pm 0.03$ | 4.03 $\pm 0.03$ | 6.05 $\pm 0.02$ |        |                               |         |
| SE       | CO(2-1)| 230.5379  | (0, 0)  | 1         | $-40.89 \pm 0.03$ | 3.97 $\pm 0.28$ | 13.74 $\pm 0.90$ | 0.16 | 1                              | 10      |
|          |        |           |        | 2         | $-44.76 \pm 0.06$ | 3.82 $\pm 0.37$ | 11.67 $\pm 0.94$ |        |                               |         |

Figure 11. 12 m CO(1-0) spectrum of HB 3 B1 (CO(3-2) spectrum is shown in Figure 10(a)) with an offset of (+10, +20) shows a broad CO line with an FWHM of 18 km s$^{-1}$ with high signal to noise. The numbers shown on the upper side are frequencies in megahertz.

The preshock velocities are adopted from the narrow peak as $V_{\text{preshock}}(\text{S1}) \approx -58$ km s$^{-1}$, $V_{\text{preshock}}(\text{S2}) \approx -40$ km s$^{-1}$, and $V_{\text{preshock}}(\text{B1}) \approx -37$ km s$^{-1}$ (see Figure 16). Because the excitation energy of CO(3-2) is low ($E_{\text{up}} = 33.19$ K), this line is thus easily excited long after the shock passes where gas temperature is cooled down. However, this excess is so narrow it resembles a Dirac-Delta function. Therefore, we remove its contribution in Figure 16.

For B1, the CO(3-2) line is broad and asymmetric, and our model estimates $V_{\text{shock}}$ of 37 km s$^{-1}$ and a viewing angle of 55$^\circ$. Here, the viewing angle is defined as the angle between the line of sight and the direction vector of the shock. Note that in the one-dimensional shock model we use here, B-field direction cannot be a constraint. The shock velocity can be approximately the beginning and the end of the line profile (i.e., the width between the two zero fluxes, from $-60$ km s$^{-1}$ to $-20$ km s$^{-1}$ in Figure 16). The line that is roughly symmetric (for example, like B2 in Figure 10), indicates the shock velocity to be approximately perpendicular to the line of sight.

The shocked gas is blueshifted relative to the ambient gas, as shown in Figure 16.

In contrast, for S1 and S2, the shocked gas (see Figures 9 and 16) is redshifted relative to the ambient gas, so the shock is moving away from us, on the backside of the SNR ($\theta = 212^\circ$ and 252$^\circ$, respectively), as listed in Table 6. The H$_2$ filament is the shell of southwest direction (see Figure 9), which is consistent with the angle being greater than 180$^\circ$. The magnetic field is largely perpendicular to the shock velocity in CJ-shock. The most narrow line profile can be for the shock penetrating the densest gas. Narrower lines at velocities far from the ambient gas can be explained by shocks into regions with a magnetic field parallel to the shock velocity, and the magnitude of the velocity shift depends upon the velocity (see Figure 6 of Reach et al. 2019, for comparison). S2 region has a higher density and a lower shock velocity than those in the S1 region.
The shocks in Regions B1–B3 and Regions S1–S2 are progressing in somewhat different directions, generally on the front and far side of the SNR, with variations due to density inhomogeneities and the detailed shape of the magnetic field. The morphology of the H$_2$ emission is highly filamentary, suggesting shock fronts in the plane of the sky, with a shock velocity perpendicular to the line of sight. Such shocks would produce lines with the limited offset in velocity with respect to the ambient gas; the lines would be wide where the magnetic field is perpendicular to the shock and narrow where the magnetic field is parallel to the shock velocity. The regions sampled by spectra B1 and B3 have large velocity offsets, and they arise from shocks that are moving toward us, on the front side of the SNR (B1 has $\theta = 55^\circ$), which is consistent with the H$_2$ thin filaments that show the arc shells in the southeastern direction (Figure 10). The presence of shocks with a wide range of angles in a small region can be explained by three-dimensional models taking into account the wrapping of the shock front around a dense obstacle (Tram et al. 2018). The changes observed in line profile shape on small scales are, we suspect, due to changes in the direction of the shock relative to the magnetic field. Small-scale changes in the magnetic field are possible due to the evolution of the shocks passing through dense regions, with the magnetic field wrapping around the denser cores. The improved 3D model with applications to the millimeter CO spectra will be presented in the future.

Future high-resolution H$_2$ line spectroscopy, such as the Stratospheric Observatory for Infrared Astronomy for rotational...
WISE show that about half of the SNR is interacting with molecular clouds. Figure 5 shows broad CO molecular lines where shocked H$_2$ is also detected. H$_2$ images critically reveal where the interaction occurs. The H$_2$ emission crucially reveals the location and energy budget of the shock passing through the region.

It is interesting that despite the half-region interaction, the radio images in the east and south still shows a relatively well-behaved symmetric shell-like morphology. In NW’s direction, the radio shell is not bright, and there is no H$_2$ emission, where the medium is likely in lower density than those of H$_2$ emitting regions. This result is consistent because optical emission is bright at the west and north, where H$_2$ emission is not detected. Interestingly, the radio shell is also weak in the direction of the southeastern shell in HB 3 where the SNR interfaces with the H II region of W3.

Several SNRs of IC 443, W28, W44, 3C391, W51C, HB 21 (references in Section 1), and G357.7+0.3 (Rho et al. 2017) clearly show BMLs which include the lines broader than 15 km s$^{-1}$. We can add the SNR HB 3 as the SNR is exhibiting BML lines. Nine SNRs have been suggested to show BMLs (Kilpatrick et al. 2016), but they are confused with many emission lines along the line of sight, and the broadening is so far only 7–10 km s$^{-1}$. High spectral resolution or higher transition lines of CO lines will be helpful to verify the interactions. There is another ~30 SNRs which show positional coincidence between the SNR and surrounding molecular clouds (Huang & Thaddeus 1986; Jiang et al. 2010). High-spatial CO observation and high transition lines are critical to verify the dynamic interactions.

HB 3 is located at a distance similar to W28 and shows a directional density gradient, as also observed in W28. HB 3 shows shock-wave interaction in the east and south, while W28 shows it in the eastern and northern directions. HB 3 is an intriguing case because it shows a beautiful and clean shock front from H$_2$ imaging. A lot of single shocks are resolved since the shock is perpendicular to the line of sight in HB 3, while the east of W28 shows shocks moving toward us and showing a mixture of multiple shock components.

9. Conclusion

1. We present the detection of shocked molecular hydrogen (H$_2$) from the SNR HB 3 (G132.7+1.3) using Palomar WIRC narrow-band imaging, the Spitzer GLIMPSE360, and WISE surveys, along with detections of broad CO millimeter lines using HHSMT. ROSAT mosaic engine image of HB 3 shows center-filled X-ray emission within a well-defined radio shell and HB 3 is classified as a mixed-morphology SNR.

2. Our near-IR narrow-filter H$_2$ 2.12 μm imaging of HB 3 using the Palomar Hale 200 inch telescope shows that the Spitzer IRAC 4.5 μm and WISE 4.6 μm emission originates from shocked molecular hydrogen, H$_2$ emission.

3. The high-resolution images with Spitzer and WISE distinguish the region structures, notably the boundary of the SNR, dense molecular clouds, and W3 complex. H$_2$ emission is observed from the east-to-south half of SNR HB 3. The morphology exhibits a butterfly (or W) shape where the southeastern part is wrapping around the H II region of the W3 complex, indicating that the SNR interacts with the molecular cloud and the H II region. The H$_2$ emission of HB 3

8. Comparison of HB 3 with Other Molecular Interacting SNRs

The molecular interaction of HB 3 is roughly half of the SNR, a position angle of 40–220 degrees from north, counter clockwise. In other words, the interacting area is from northeast to east and south to southeast. H$_2$ images from Spitzer and ground-based telescopes for vibrational lines will enable us to compare the shock properties—shock kinematics, density, shock age, and the strength of magnetic field—between H$_2$ and CO emitting gas.
shows thin, sharp filamentary structures, and bright emission at the southern and eastern shell.

4. Broad lines of molecular CO\((3-2)\) and CO\((1-0)\) are detected from the southern shell of HB 3 and at the interaction sites with molecular clouds and near the W3 complex. The widths of the broad lines are 8–20 km s\(^{-1}\), and the profiles change on small scales, \(\sim 10''–60''\). HB 3 stands apart from other mix-morphology SNR in that we also observe narrow lines, \(\sim 8\) km s\(^{-1}\) (in FWHM), which might imply that individual shocks are being resolved in dense gas.

5. We apply the Paris–Durham shock model and reproduce the CO line profiles. The inferred shock velocity of 20–40 km s\(^{-1}\), a density \(6 \times 10^{3}–2 \times 10^{4}\) cm\(^{-3}\), and the viewing angle indicates that H\(_2\) emission in the SE is on the front side of the SNR, while the southern shell is on the backside of the SNR.

JWST with high-spatial-resolution imaging on sub-arcsecond (0.1'' with the Mid-Infrared Instrument) to two decimals (\(\sim 0.05''\) with NIRCam) scales would be able to resolve multi-shocks and 3D bending geometry that is just beyond our current observations and modeling techniques. Spitzer spectroscopy observations of HB 3 were not taken. The JWST spectroscopy can provide rotational transition lines of H\(_2\) lines, which will enable us to probe excitation temperatures and the age of the shock of the H\(_2\) emitting regions.

| Position | Shock Velocity \(V_s\) (km s\(^{-1}\)) | Density \(\rho\) (cm\(^{-3}\)) | Magnetic Field \(B\) (\(\mu\)G) | Viewing Angle \(\theta\) (\(^\circ\)) | Preshock Velocity \(V_{\text{preshock}}\) (km s\(^{-1}\)) | Figure # |
|----------|-----------------------------------|--------------------------------|-----------------|----------------|----------------|---------|
| S1       | \(\sim 37\)                        | \(\sim 6 \times 10^{3}\)     | \(\gtrsim 252\) | \(\sim 215\)  | \(\sim 58\)  | 8, 9, 16 |
| S2       | \(\sim 22\)                        | \(\sim 2 \times 10^{4}\)     | \(\gtrsim 212\) | \(\sim 230\)  | \(\sim 40\)  | 8, 9, 16 |
| B1       | \(\sim 37\)                        | \(\sim 6 \times 10^{3}\)     | \(\gtrsim 252\) | \(\sim 55\)   | \(\sim 37\)  | 8, 10, 11, 16 |

Note. \(^a\) The viewing angle is defined as the angle between the line of sight and the direction of shock. The angles of 215\(^\circ\) and 230\(^\circ\) are the shocks moving away from us, on the backside of HB 3. The angle of 55\(^\circ\) is the shock moving toward us, on the front side of HB 3.
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Facilities: Spitzer, WISE, Palomar Hale 200 inch (WIRC), Arizona Observatory HHSMT and 12 m Kitt Peak.

Software: CLASS and GILDAS, IRIF, IDL, Python, Astropy.

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Figure 16. The best CO(3-2) line profile predicted from our shock model, compared to observations for the S1 position (top panel), the S2 position (middle panel), and the B1 position (bottom panel). The profile intensity is normalized to the observations. The line emission at $V_{lsr} \sim 0$ km s$^{-1}$ is from gas in the line of sight and unrelated to HB 3.
