SHOCKED MOLECULAR GAS IN THE SUPERNOVA REMNANTS W28 AND W44: NEAR-INFRARED AND MILLIMETER-WAVE OBSERVATIONS

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ABSTRACT

High-resolution millimeter-wave (CO, CS, and HCO+ rotational lines) and near-infrared (H$_2$ 2.12 $\mu$m ro-vibrational and Fe II fine-structure lines) observations of the supernova remnants W28 and W44 reveal extensive shocked molecular gas, where supernova blast waves are propagating into giant molecular clouds. New CO observations were carried out with the IRAM 30 m and Arizona Radio Observatory 12 m telescopes, and the near-infrared observations were with the PFIRCAM and Wide-Field Infrared Camera on the Palomar Hale 200 inch (5.08 m) telescope. The near-infrared observations reveal shocked H$_2$ emission from both supernova remnants, showing intricate networks of filaments on arcsecond scales, following the bright ridges of the radio shells. The emission is particularly bright in the northeastern, southern, and western parts of W44 and in the eastern bar in W28. The H$_2$ emission reveals some bright, clumpy structures, as well as very thin filamentary structures likely to be individual shock fronts seen edge-on. The high-resolution IRAM CO(2 $\rightarrow$ 1) and CS(2 $\rightarrow$ 1) spectra clearly distinguish between the shocked and preshock gas for most of the supernova remnants. Some of the CO spectra appear to have multiple components, but the less optically thick $^{13}$CO lines clearly demonstrate that the CO(2 $\rightarrow$ 1) lines are broad, with deep absorption dips caused by cold, dense gas in the line of sight. The CO and CS line widths, indicative of the shock speed, are 20–30 km $s^{-1}$.

Both the near-infrared and millimeter-wave emission are attributed to shocks into gas with density higher than $10^{3}$ cm$^{-3}$. Individual shock structures are resolved in the H$_2$ emission, with inferred edge-on shock thicknesses of $\approx$10$^{17}$ cm, consistent with nondissociative shocks into gas densities of $10^{3}$–$10^{4}$ cm$^{-3}$. Bright 1720 MHz OH masers are located within the shocked H$_2$ gas complexes and highlight only localized areas, where the conditions for masing are optimal. The H$_{\alpha}$ and X-ray emission, which trace hotter shocked gas, have morphologies very different from the radio. We find a detailed correlation of the radio and H$_2$ emission for some long filaments, indicating cosmic-ray acceleration or reacceleration due to shocks into moderately dense gas. Compared to the interclump gas and the very dense cores, the synchrotron emissivity of the moderate-density (CO emitting) medium is highest, which explains the radio-H$_2$ correlation and the very bright radio emission of these two supernova remnants despite their relatively advanced age. The different morphologies of these two remnants at different wavelengths are explained by the highly nonuniform structure of giant molecular clouds, with low-density ($\sim$5 cm$^{-3}$) gas occupying most ($\sim$90%) of the volume, moderate-density gas ($\sim$10$^{3}$ cm$^{-3}$) gas occupying most of the rest of the volume, and dense gas in the cores.

Subject headings: ISM: individual (W28, W44) — ISM: molecules — shock waves — supernova remnants

1. INTRODUCTION

W28 and W44 are two supernova remnants in molecular clouds. They are very bright radio sources—the sixth and seventh brightest remnants in the Green (2001) catalog—with shell-like morphologies (Dubner et al. 2000; Jones et al. 1993), located adjacent to giant molecular clouds with which they have been suspected to be interacting (Wootten 1981; Denoyer 1983). W28 and W44 are also paradigms of the new class of “mixed-morphology” supernova remnants, whose shell-like, nonthermal radio emission contrasts sharply with centrally filled, thermal morphology” supernova remnants, whose shell-like, nonthermal morphology” supernova remnants. Both remnants have mean radii of 11 pc. The radio shell of W44 is noncircular, being elongated north–south, and brighter on the eastern side than elsewhere. The radio shell of W28 is much brighter and better defined on its northern side than elsewhere.

W44 is host to the pulsar B1853+01, which is almost certainly the remnant of the progenitor star (Wolszczan et al. 1991). The presence of the pulsar yields two key clues to the nature of W44. First, it must be the result of a core-collapse supernova from a progenitor with a mass between 8 and 20 $M_\odot$: a smaller progenitor would not form a neutron star (Woosley 1987; Wheeler 1981), while a larger one would form a black hole instead (Fryer 1999). The spectral type of the progenitor, when on the main sequence, would have been between B4 and O8. If such a star were surrounded by material with a density of 1 or $10^3$ cm$^{-3}$, the H II region would have been smaller than 2 or 0.02 pc, respectively. Thus, the progenitor would have had little influence on its parent molecular cloud on the size scales of the present supernova remnant (Spitzer 1978). Second, the age of the remnant is probably comparable to the spin-down age of the pulsar, 2 $\times$ 10$^4$ yr (Wolszczan et al. 1991). PSR B1853+01 also produces relativistic particles and excites a wind nebula visible in the radio (Frail et al. 1996) and X-ray (Petre et al. 2002). A relatively young pulsar, PSR B1758–23, is near W28 but outside the remnant (Kaspi et al. 1993); the weight of current evidence suggests that this pulsar is not related to W28 (Claussen et al. 2002). The association of W28 with molecular clouds and its radio/X-ray morphology suggest the progenitor may also have been a core collapse, in which case the stellar remnant should now be a radio-quiet neutron star or a black
hole; however, the supernova could also have been a Type I, coincidentally close to a molecular cloud.

Gamma-ray sources, detected with the Compton Gamma Ray Observatory using EGRET, have been associated with W28 and W44 (Esposito et al. 1996); the updated associations using the third EGRET source catalog (Hartman et al. 1999) are 3EG J1800–2338 for W28 and 3EG J1856+0114 for W44. The angular resolution in γ-rays is insufficient (0.3") to pinpoint their origin. The W28 source is south of the remnant center in a relatively radio-faint part of the remnant. The W44 source is located within the remnant, with the pulsar included in its error circle. No TeV photons were detected from W28 using CANGAROO, so the source spectrum must turn off between GeV and TeV energies (Rowell et al. 2000).

Both W28 and W44 have extensive evidence for interaction with molecular clouds. Early observations (Wootten 1981; Denoyer 1983) showed molecular gas near or possibly in the remnant, but the sensitivity, resolution, and available millimeter-wave receivers (limited to the 3 mm band) were inadequate to clearly reveal a direct interaction with the molecular clouds. X-ray observations showed that these two remnants are filled with a large amount of relatively dense (n ~ 1 cm⁻³), hot gas. The X-ray morphologies contrast markedly with the shell-like radio morphologies, making W28 and W44 members of the mixed-morphology class; the existence of a significant amount of material inside the remnant is attributed to interaction of the remnant with relatively dense gas (Rho et al. 1994; Rho & Petre 1998).

The most clear-cut evidence for interaction between the supernova remnants and molecular clouds is the detection of emission from the shocked molecules themselves. The molecules can be directly detected in four ways: millimeter-wave emission lines with line widths much greater than those of cold gas, OH 1720 MHz maser emission, far-infrared line emission, and near-infrared H₂ emission. (1) Broad molecular line (BML) emission has clearly been detected from W44 using CO(1 → 0) and CO(2 → 1) observations (Seta et al. 1998) and from W28 using a small telescope to map the remnant in the CO(3 → 2) line (Arikawa et al. 1999). The line widths of ~20–30 km s⁻¹ FWHM, with maximum extents up to 70 km s⁻¹ in some locations, clearly distinguish the shocked gas from the cold, ambient gas. (2) OH 1720 MHz maser emission has been detected from W28 (Frail et al. 1994a) and observed in more detail for both W28 and W44 (Claussen et al. 1997) using the NRAO Very Large Array (VLA). These 1720 MHz OH masers have been interpreted as spots of amplified radio emission through clumps of OH gas with densities and temperatures characteristic of modest-density (n ~ 10³ cm⁻³) gas that has been shocked by modest-velocity (v ~ 20 km s⁻¹) nondissociative shocks (Lockett et al. 1999; Warde & Yusef-Zadeh 2002). The brightest maser emission arises from small spots with high amplification. VLBI observations yield upper limits to the angular sizes from 0.05 to 0.18, with very strong measured magnetic field strengths of 2 mG (Claussen et al. 1999). Recent radio spectral observations of W28 showed that normal, thermal absorption in the main OH lines can trace the shocked gas, because the absorption lines have broad line widths; faint satellite line emission (probably weak masers) has a narrow line width and covers much more area than just the maser peaks (Yusef-Zadeh et al. 2003b). There now appears to be a strong association between mixed-morphology supernova remnants and maser-emitting supernova remnants (Yusef-Zadeh et al. 2003a), suggesting that while W28, W44, and IC 443 may be prototypes of molecular-cloud-interacting supernova remnants, the total number could be much higher. (3) Highly excited far-infrared CO(16 → 15) and mid-infrared H₂ [(S(3) and S(9))] emission, together with all the atomic fine-structure lines expected from shocks into moderate-density gas, was detected from W28 and W44 using the Infrared Space Observatory (Reach & Rho 1998, 2000). (4) Near-infrared H₂ emission is predicted to be one of the main coolants of shocks in dense gas (Draine et al. 1983). Bright H₂ 2.12 μm emission has been detected from IC 443 (Burton et al. 1988; Rho et al. 2001) and 3C 391 (Reach et al. 2002). Near-infrared emission from W28 and W44 has not yet been reported, and one of the main goals of this paper is to present our new observations and their implications.

Some relevant theoretical models have recently been published. A model was developed specifically for W44, attempting to explain its observed features across an exceptionally wide range of observed properties, analytically by Cox et al. (1999) and numerically by Shelton et al. (1999). They explain many properties of the remnant as the result of a shock propagating into an essentially uniform medium with a density of n₀ = 6 cm⁻³. The hot interior of the remnant is relatively dense in their model, n_{int} = 1 cm⁻³, as required to explain the centrally filled X-rays. This model does not include denser gas. Chevalier (1999) published a model of a supernova remnant in a molecular cloud. This model is generally similar to that of Cox et al. (1999), because most of the observable properties are due to shocks in the interclump gas with a preshock density of n₀ = 4–5 cm⁻³; however, Chevalier (1999) also discussed some of the consequences of denser material. Based on these models, one would infer that some giant molecular clouds are predominantly composed of material of much lower density than is capable of producing the features that define giant molecular clouds, such as CO emission, gravitational binding, and star formation. Low-density (n < 10 cm⁻³) material either is diffuse (tenuous, transient, and unbound) or is present together with other material that we know of as the molecular cloud and that dominates the mass and most other observable properties. How can these two different views of molecular clouds be reconciled?

The observations of W28 and W44 provide a special opportunity to determine the structure of giant molecular clouds by studying the results of 10⁵¹ erg explosions inside the clouds. By observing the results of a supernova explosion in the cloud, we can determine whether (1) the shock is expanding unimpeded, as would occur if the filling factor of dense gas were very small and there were no interclump gas, (2) the shock is propagating primarily in the dense gas, as would occur if its filling factor were large, or (3) the shock is not significantly affected by the dense gas (having a low filling factor) but propagates primarily into low-density, interclump gas. A wide range of supernova remnant morphologies is possible, and at least three preshock density regimes have been inferred from the range of gas coolants in far-infrared spectra (Reach & Rho 2000). By observing the shocked molecular gas directly, and at unprecedented sensitivity and resolution, we can better explain the current remnant morphology and begin to attribute different aspects of the supernova remnants to specific properties of the parent molecular clouds.

After this introduction, we summarize the new observations that we performed: wide-area millimeter-wave CO observations, high-resolution millimeter-wave CO and CS observations, and near-infrared H₂ observations. Then we describe the results for each remnant in detail. With all the observations and results in hand, we then compare the shocks as traced by near-infrared and millimeter-wave emission and attempt to separate preshock
gas, gas experiencing dissociative shocks, and gas experiencing nondissociative shocks. We discuss the implications of our observations for the origin of synchrotron radiation from mature supernova remnants and for cosmic-ray acceleration. Finally, we explain why the properties of the ambient medium that we infer from infrared and millimeter observation of shocked clumps and filaments are so different from the properties inferred from X-ray and radio observations of the supernova shell and hot interior.

2. OBSERVATIONS

2.1. CO Survey Data

The parent clouds with which the remnants are interacting, and from which the progenitors presumably formed, can be seen in CO surveys of the Galactic plane. Previous studies of these remnants have referred to a wide range of structures in the interstellar medium as being associated with the remnants, including H I emission and absorption observations (Knapp & Kerr 1974; Denoyer 1983; Velázquez et al. 2002) and limited CO mapping (Dickel et al. 1976; Wooten 1977, 1981; Seta et al. 1998), which trace parts of the clouds but do not reveal their full extents.

Figure 1 shows the CO images of the parent molecular clouds. The CO data are from the reprocessed survey (Dame et al. 2001), including the inner Galaxy data originally from Bitran et al. (1997). W44 is located in a well-defined, giant molecular cloud that is clearly distinguished from the surrounding material; the cloud is centered at $l = 35^\circ.0$, $b = -0^\circ.7$, $v = 44$ km s$^{-1}$, with a radius of 58 pc and a total mass of $1.8 \times 10^6 M_\odot$ (Dame et al. 1986). The parent cloud for W28 can be discerned in the CO data cube for the inner Galaxy (Dame et al. 2001); it is centered at $l = 6^\circ.6$, $b = 0^\circ.0$, $v = 19$ km s$^{-1}$, with a diameter of $\sim 25$ pc and a mass of $1.4 \times 10^6 M_\odot$. The similar radio and X-ray morphologies, ages, locations near molecular clouds, and parent molecular cloud properties make W44 and W28 a good pair of remnants to study together.

2.2. NRAO/Steward Observatory 12 m Observations

Observations were performed in 1997 March and 2002 November with the 12 m millimeter-wave telescope on Kitt Peak. The observations were made using the on-the-fly technique, whereby the telescope was slewed in right ascension at a constant rate of $30''$ and $10''$ s$^{-1}$, and spectra were taken at 0.1 s intervals, which finely samples the telescope beam of $53''$ and $26''$ at 115 and 230 GHz, respectively. In 1997 March, the eastern half of W44 was mapped in the CO(1 $\rightarrow$ 0) line (115 GHz), and regions surrounding some of the apparent shock interactions in W44 and W28 were mapped in the CO(2 $\rightarrow$ 1) line (230 GHz). In 2002 November, a complete map of W44 was made in the CO(2 $\rightarrow$ 1) line.

The CO(1 $\rightarrow$ 0) observations of W44 reveal extensive emission covering the entire region. On large scales, the dominant feature is the giant molecular cloud at a velocity of 43 km s$^{-1}$, with lines that are typically 10 km s$^{-1}$ wide (with substructure); this is consistent with the overall giant molecular cloud described above. There are no clear indications of shock-broadened molecular lines from the CO(1 $\rightarrow$ 0) observations; most of the broadening is due to the same combination of gravity, turbulence, and magnetic pressure that generates the line widths observed from this and other giant molecular clouds.

The CO(2 $\rightarrow$ 1) observations of both W28 and W44 also reveal extensive emission, with a great deal of structure both spatially and spectrally. The separation of the emission into parent cloud, shocked gas, and foreground absorption requires understanding of the geography of each remnant, which we describe in §§3 and 4 for W44 and W28, respectively.

2.3. IRAM 30 m Observations

On 1997 September 16–22, we observed W44 and W28 using the IRAM 30 m telescope on Pico Veleta, Spain. Some spectra were also obtained from our earlier 1996 November 22–29 observing run. These observations cover small portions of the remnants, selected based on the 12 m maps and the CO(1 $\rightarrow$ 0) maps of Seta et al. (1998). The observing procedure, calibration, and data reduction for these observations were the same as described for our previous observations (Reach & Rho 1999). Three receivers were used to simultaneously observe three different spectral lines at 1.3, 2, and 3 mm. The weather during the 1997 observing run included freezing rain but had usable periods of haze. The receivers were tuned to the CS(2 $\rightarrow$ 1), CS(3 $\rightarrow$ 2), and CO(2 $\rightarrow$ 1) lines, with system temperatures of typically 330, 520, and 1300 K. Very few lines of sight produced detectable CS(2 $\rightarrow$ 1), so we tuned the 3 mm receiver to SiO(2 $\rightarrow$ 1, $v = 0$) for the last half of the run. The weather during the 1996 run was better, which allowed CS(3 $\rightarrow$ 2) and CS(5 $\rightarrow$ 4) observations.
2.4. Palomar Observations

On 2001 July 12–13 and 2002 August 16–17, we observed portions of W44 and W28 (and other supernova remnants) using the PFIRCAM on the Hale 200 inch (5.08 m) telescope on Mount Palomar. The PFIRCAM has a 256 × 256 pixel array, with a pixel scale of 0.′′494 at the f/3.3 prime focus. In 2001, the weather was hazy, with 15° seeing. In 2002, the weather was very good, with 08′ seeing on both nights. Two fields (the western portion of W44, and the eastern portion of W28) were re-observed using the new Wide-Field Infrared Camera (WIRC), a 2048 × 2048 camera with 0.′25 pixels, on 2003 August 9, also under very good conditions (0′′9 pixels). For W28 we used the VLA interferometric internal structure of the remnant. The astrometry was determined using the PFIRCAM images: specifically, faint ghost images located 13′′ from very bright sources (nearly 1% wide in PFIRCAM and 1.5% in WIRC). Smaller regions were observed in other narrow (1%/2 pixel) filters or Paβ (1%/2 cm−2 sr−1). Therefore, continuum substraction was neither needed nor performed on the observations presented below. Some artifacts remain in the PFIRCAM images: specifically, faint ghost images located 13′′ northwest (61° position angle) from very bright sources (nearly impossible to discern in the published images because of the huge number of real stars that are brighter than the ghost images), and rays of stray light when stars fall on the edge of the detector (some were masked by hand and appear as polygonal cutouts). The observations have a noise level of (0.5–1) × 10−7 ergs cm−2 sr−1 pixel−1. The absolute calibration is accurate to better than 20%, and the narrow band directly measures the surface brightness of the shocked gas except in positions containing stars.

2.5. Other Observational Data

To complement the new CO and molecular data, we requested radio and optical images from other researchers. Supernova remnants are most closely traced by nonthermal radio continuum emission, so the best maps of overall remnant geography are low-frequency but high-resolution radio images. For W44 we used the VLA image of Jones et al. (1993) at a frequency of 1465 MHz; the 15′′ angular resolution and low (1.5 mJy beam−1) noise of this image clearly reveal the filamentary internal structure of the remnant. The astrometry was corrected by comparing with the high-resolution radio image of the W44 pulsar wind nebula published by Frail et al. (1996), using the pulsar as a guide point. For W28 we used the VLA image of Dubner et al. (2000) at a frequency of 328 MHz; the 92′′ × 52′′ angular resolution is not good, but the remnant is cleanly separated from thermal emission. We compared this image with the portion of the Frail et al. (1994b) image that covered W28 serendipitously and found very good correspondence with the remnant features, as expected.

Hα images of W28 and W44 were created by combining digitized, deep (3 hr) plates taken at the 48 inch (1.22 m) UK Schmidt telescope and provided as part of the SuperCOSMOS Hα Survey (Parker &Phillips 1998; Malin 1998; MacGillivray 1998). The line filter has a 1% width centered on 6590 Å. Images through the narrow continuum filter show no extended emission, so we did not subtract them from the Hα images used here. To verify the astrometry, we compared the reprojected, combined Hα mosaic with the Digitized Sky Survey (DSS) and Henry Draper (HD) catalog stars; the DSS and HD positions were within 1′′, while there was an offset of 9′′ in the Hα image, which we corrected. The Hα emission from W28 has been described before by Van den Bergh et al. (1973), but the new image is much deeper and has been digitized, enabling a detailed comparison with the radio and other images.

3. RESULTS FOR W44

To get oriented within W44, Figure 2 shows the radio image together with outlines of the observed regions. The radio emission arises from a limb-brightened shell that breaks into prominent filaments, many of which appear to emanate from the southeast. The radio emission is generally much brighter in the eastern hemisphere, but there is a knot of bright radio emission in the westernmost portion of the shell as well.

3.1. Millimeter-Wave Results for W44

The CO(2 → 1) observations with the 12 m telescope covered the entire remnant (with low sensitivity). Figure 3 shows...
intensity maps in different velocity ranges. Each velocity range corresponds (in central velocity and width) to one of the several spectral components that are present in this field. The giant molecular cloud associated with W44 appears in Figures 3e and 3f. The cloud clearly extends past the edges of our image, in particular to the north and east, consistent with the giant molecular cloud in Figure 1. The spectrum averaged over the portion of the giant molecular cloud in our image reveals a simple, Gaussian line profile centered at 46.6 km s\(^{-1}\), with a line width of 4.1 ± 0.2 km s\(^{-1}\), a peak brightness temperature of 6.9 K, and a line integral \(W[\text{CO}(2 \to 1)]\) of 30 K km s\(^{-1}\). Using \(N(\text{H}_2)/W[\text{CO}(1 \to 0)] = 3 \times 10^{20} \text{ cm}^{-2} \text{ K}^{-1} \text{ km}^{-1} \text{ s}^{-1}\) (Bloemen et al. 1986), this cloud has a column density of \(N(\text{H}_2) = 1.1 \times 10^{22} \text{ cm}^{-2}\). The column density inferred from absorption of X-rays from the interior of the remnant is \(N(\text{H}) = 2 \times 10^{22} \text{ cm}^{-2}\) (Rho et al. 1994); assuming most of the gas is molecular, this would correspond to \(N(\text{H}_2) = 1 \times 10^{22} \text{ cm}^{-2}\) and agree well with the column density inferred from the CO observations, suggesting that much of the parent cloud is in front of the remnant. The velocity of this cloud is consistent with Galactic rotation at the longitude and distance of W44. This is the ambient molecular cloud with which W44 is interacting and from which the progenitor star probably formed.

The northeastern ridge of bright radio emission is closely parallel to the surface of the molecular cloud as traced in Figure 3e. It appears that the W44 progenitor exploded within, and just to the west of the center of, its parent molecular cloud. There is ambient gas from the parent all around the remnant. Figure 3f
shows a piece of the west of the remnant; the interaction of the remnant with this gas probably explains the very bright, western radio knot, for which we present new observations of shocked H$_2$ below. The presence of ambient molecular gas all around W44 makes it a special case of a supernova within a molecular cloud. A similar situation was found in 3C 391, although its progenitor was relatively closer to the edge of its parent molecular cloud or even just outside (Wilner et al. 1998). Before the supernova, the progenitor of W44 would have generated only a very small H II region, even if it had been an O star, because the surrounding medium is relatively dense.

In addition to the ambient cloud, the CO observations reveal several other features that can be distinguished in the maps at velocities different from that of the ambient cloud. Figure 3 shows two very distinct clouds at 95 km s$^{-1}$. The presence of the broad emission line confirms that the positions they identified as having prominent wings do indeed have broad line-of-sight absorption is stronger for the 1$\rightarrow$0 transition, which can be absorbed by cold gas with substantial populations in the ground state, than for the 2$\rightarrow$1 transition. Neither of these effects is a dramatic improvement, because the $J = 2$ level can be excited by the unshocked gas (leading to narrow absorption lines from the cold gas along the line of sight) and the $J = 1$ level has a substantial population in the unshocked gas (leading to narrow absorption lines from the cold gas along the line of sight). However, the combined effects, together with the higher angular resolution at the higher observing frequency, make these new data significantly cleaner in tracing the shocked gas.

To investigate the distribution of the shocked gas relative to the unshocked gas, we made small maps around a few positions that showed broad emission lines. Figure 5 shows the CO(2$\rightarrow$1) spectrum for a position near W44 OH E with a clear, broad component and a superposed narrow emission component. The FWHM of the narrow component is 5.2 km s$^{-1}$, typical of the ambient molecular cloud around W44. The

### Table 1: Positions for Maps Made at the IRAM 30 m

| W44 Position | R.A. (J2000.0) | Decl. (J2000.0) | $\Delta$R.A. (arcsec) | $\Delta$Decl. (arcsec) | Description | References |
|--------------|---------------|----------------|----------------------|------------------------|-------------|------------|
| OH E........... | 18 56 28.1    | +01 29 59      | 0                    | 0                      | OH maser    | 1          |
| OH F........... | 18 56 36.7    | +01 26 32      | 129                  | -207                   | OH maser    | 1          |
| PW1........... | 18 56 12.7    | +01 26 25      | -230                 | -214                   | Prominent CO (1 $\rightarrow$0 wing; “Wing 1”) | 2; 3 |
| PW3........... | 18 56 11.7    | +01 27 55      | -246                 | 124                    | Prominent CO (1 $\rightarrow$0 wing; “Wing 1”) | 2; 3 |
| OH A........... | 18 52 55.2    | +01 29 51      | 0                    | 0                      | OH maser    | 1          |
| OH B........... | 18 56 01.2    | +01 12 47      | 0                    | 0                      | OH maser    | 1          |
| OH C........... | 18 56 03.7    | +01 08 44      | 37                   | -243                   | OH maser    | 1          |
| OH D........... | 18 56 29.4    | +01 20 26      | 0                    | 0                      | OH maser    | 1          |

Notes.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds. The reference position is listed as (412º, -3621º) from W44 OH E.

References.—(1) Claussen et al. 1997; (2) Seta 1995; (3) Seta et al. 2004.
FWHM of the broad component is 30.5 km s\(^{-1}\), which is far wider than that of the ambient gas and is due to shocks with speeds equal to or greater than (because of projection) 30.5 km s\(^{-1}\) into the dense gas. The amplitude of the broad component near W44 OH E varies significantly from position to position, while the narrow component is widespread. The location where the broad component is brightest is not coincident with an OH maser. A similar result was found in the BML region in 3C 391, where an OH maser is located between the peaks of the broad and narrow components (Reach et al. 2002).

Another position of interest is W44 PW1, the location of a “prominent wing,” also called “Wing 1,” which was found from Nobeyama 45 m CO(1 – 0) observations (Seta 1995; Seta et al. 2004). Figure 4h shows the CO(2 – 1) spectrum and the \(^{13}\)CO(1 – 0) spectrum toward this position. The CO(2 – 1) emission is clearly broad but has a double-humped structure that could be mistaken for multiple, moderately broad components along the line of sight. The double-humped structure is actually due to a deep absorption trough cut into a single broad emission component. The \(^{13}\)CO(1 – 0) emission, which traces the total column density and is dominated by the cold gas along the line of sight, matches very well the center and width of the apparent “notch” cut out of the CO(2 – 1) spectrum. The optical depth of the absorbing CO in the \(J = 1\) level must be \(\tau > 1\) to produce this trough. Such an optical depth is consistent with the column density of the parent molecular cloud (and its location in front of the remnant) as discussed above. Inspecting the spectra near W44 PW1, the narrow absorption component transforms into a

![Diagram of spectra](image-url)
narrow emission component in locations where there is no BML emission. This can be explained by a combination of geometry and physical conditions. When there is bright emission from hot, shocked gas behind cold, unshocked gas, an absorption component appears. Then, when the column density of shocked gas is small enough that its brightness temperature is lower than that of the shocked gas, or the cold gas is behind the hot gas, the narrow component appears in emission.

The depth, velocity, and location of the molecular absorption features suggest that they are due to preshock gas. Figure 6 shows high-quality spectra of CO(2 → 1), HCO+(1 → 0), and 13CO(1 → 0). The HCO+ spectra are similar to the CO(2 → 1) spectra, with deep absorption near the line center and even broader wings. The HCO+ line is even more susceptible to absorption than CO(2 → 1) because it is a ground-state transition with a larger dipole moment. The optical depth in the core of the HCO+(1 → 0) line is \( \tau_c = 2 \times 10^{-2} \), with a width of \( \beta = 10 \text{ km s}^{-1} \) and consisting of multiple components. The required column density of HCO+ in the ground state is \( N_{\text{HCO}^+} = 1.03 \times 10^{17} \text{ cm}^{-2} \), which amounts to \( 2 \times 10^{13} \text{ cm}^{-2} \). If the abundance of HCO+ relative to H2 is \( 2 \times 10^{-9} \), typical of molecular clouds (Liszt & Lucas 2000), then the inferred column density in the absorbing cloud is \( N_{\text{H}_2} \simeq 1 \times 10^{22} \text{ cm}^{-2} \). This column density agrees very well with that of the parent molecular cloud, based on the CO(1 → 0) brightness and X-ray absorption. Because it is at the same velocity and spatial location as the remnant, they must be close together, with the absorbing gas being the unshocked portion of the parent molecular cloud along the line of sight.

The CO emission in the southern portion of W44 was observed in some detail. It appears as a broad-line region in the NRAO 12 m observations: in Figure 7, it appears as a roughly north-south filament starting just inside the southernmost boundary of the remnant. The region contains the maser complexes W44 OH B and W44 OH C. The area mapped with the IRAM 30 m is indicated in Figure 2 as a dashed box labeled "CO [30 m]." Figure 7 shows the grid of spectra, which vary dramatically from position to position. A broad emission line is clearly evident in a region extending from offsets of (0, 80) to (80, −260). In the spectra at the top of Figure 7, the emission arises from a set of narrow components. It is possible that this is actually broad-line emission being absorbed by foreground gas, as was found for W44 PW1, W44 PW3, and W44 OH F, but we only have the 13CO or HCO+ observations to disentangle the absorption and emission for a few lines of sight in the remnant. The angular resolution of the 30 m telescope in the CO(2 → 1) line is about 10''5, much smaller than the region over which broad emission lines are observed, so it is clear that the emitting

![Fig. 6.—12CO(2 → 1), HCO+(1 → 0), and 13CO(1 → 0) spectra toward three positions in W44. In each panel, the lower spectrum is HCO+(1 → 0), multiplied by a factor of 3 and shifted downward by 5 K; the middle spectrum is 12CO(2 → 1); and the upper spectrum is 13CO(1 → 0), inverted and multiplied by a factor of 2 and shifted upward by 20 K. In (a) and (b), the deep troughs in the 12CO(2 → 1) and HCO+(1 → 0) spectra near the parent cloud velocity (dashed line) align with the peaks in the 13CO(1 → 0) spectrum, suggesting that cold gas in front of the shocked region absorbs the hot, shocked gas.](image)

![Fig. 7.—Grid of spectra near W44 OH B. The grid is labeled with the offsets (in arcseconds) east and north of the nominal position of W44 OH B. There are both wide and narrow components throughout this region. The bottom of the figure covers the edge of the remnant, and the bottom right is somewhat outside the remnant, giving an idea of the baseline, random emission around the remnant. Around (0, 80), the emission appears to have two medium-wide components, but this is probably due to absorption by cold gas in front of the remnant. The range of appearances of these spectra is due to a complicated mix of emission and absorption with different angular distributions and velocity widths. There are two OH masers in this region, at (0, 0) and (37, −243).](image)
regions are extended. The profiles tend to have a wider wing on the low-velocity side, suggesting that the gas is being accelerated toward us.

3.2. Near-Infrared Results for W44

Turning to the near-infrared observations, the 2.12 μm H2 images are striking in appearance, with an intricate network of filaments and some isolated bright clumps. The three regions that were observed in the near-infrared also contain regions with bright O i 63 μm emission (Reach & Rho 1996), OH masers (Claussen et al. 1997), and BMLs (Seta et al. 2004). In the W44 northeastern image (Fig. 8), a ridge of H2 emission follows the edge of the radio supernova remnant, which runs diagonally across the upper left portion of the image. The H2 emission contains bright filaments and arcs, as well as a more diffuse component that generally envelops the brighter features. Some of the filaments are extremely narrow and probably represent individual shock fronts seen close to edge-on; these are discussed in § 5.4 below. The other structures and the diffuse emission are probably an amalgam of multiple shock fronts seen from a range of angles. Significant shocked H2 emission is detected interior to the radio shell, for example, in the lower central portion of the image.

The W44 southern image (Fig. 9, gray scale; Fig. 10, color) is the most detailed, having 4 times as much integration per pixel as the other H2 images. Two bright sets of filaments run diagonally across the field, with fainter filaments (all in the same general direction) distributed throughout the field. A very bright knot of H2 emission lies just below the upper filament in Figure 9. This is not a star or an artifact; it is just burned out in the gray-scale image. There are some narrow filaments that appear to be individual edge-on shock fronts, but for the most part the bright filaments have significant substructure, indicating that they comprise multiple shock fronts.

The W44 western field (Fig. 11) contains some very bright filaments, again roughly parallel to the edge of the remnant, which runs roughly north-south at this location. It is possible to see individual shock fronts in this image; counting across the image along a single line (from the upper left to the lower right), there are at least 15 individual shock fronts. This shows clearly that the preshock medium was highly structured, with gaps between regions containing gas with density appropriate to generate bright H2 after being shocked.

4. RESULTS FOR W28

An orientation chart showing the regions observed toward W28 is shown in Figure 12. The main geographical features of W28 are a semicircular radio shell that is brightest in the north and east and a bar (or inner shell) that extends east-west. The observed regions include most of the OH masers (Claussen et al. 1997), the bright radio ridges, and the CO(3 → 2) ridge (Arikawa et al. 1999).

4.1. Millimeter-Wave Results for W28

The 12 m CO observations covered a 9' × 13' region centered on the bright eastern radio ridge, containing many OH 1720 MHz masers (Frail et al. 1994a). Figure 13 shows a set of velocity-integrated images. BML regions are those that appear in multiple images, in particular, those away from the line core. Five BML regions can be identified in these images; Table 2 lists their positions and Gaussian fits to the line profiles. The BML regions are even more easily seen in the position-velocity images; Figure 14 shows position-velocity slices through the spectral data. The exceptionally wide velocity dispersion of the BML regions compared to the ambient gas (which has a typical width of < 7 km s⁻¹ FWHM) is evident. It is also evident that the BML regions are well-defined peaks. There is more extensive, broad-line-emitting gas, but the BML regions in Figures 13 and 14 are clumps (probably containing significant structure unresolved in our 30'' beam). A position-velocity slice through the northern radio shell in CO(3 → 2) was shown by Arikawa et al. (1999; their Fig. 2), and their CO(3 → 2) image (their Fig. 3) shows extended BML emission, so the peaks listed in our Table 2 are only a subset of the BML regions in W28.

The IRAM 30 m observations of W28 reveal the bright CO emission at higher angular resolution. Figure 15 shows a grid of spectra centered on some of the brightest CO emission, including the broad-line positions BML3 and BML4. The broad-line emission is widespread, and it is deeply cut by narrow absorption at approximately the same central velocity (8 km s⁻¹). The absorption is particularly deep toward W28 BML4, with an optical depth of more than 1 and a width of ~1 km s⁻¹ FWHM. The absorption is patchy, but cold gas at this velocity is present throughout the region; emission lines from the cold gas are seen in the spectra with weaker broad-line emission. Three
Fig. 9.—$H_2$ 2.12 $\mu$m image of the southern portion of W44 (Map 2). The portion of the supernova remnant covered by this image is indicated in Fig. 2. The clump of exceptionally bright $H_2$ emission discussed in the text is indicated by the black rectangle.
Fig. 10.—Color version of the H$_2$ 2.12 \textmu m image of the southern portion of W44 (Map 2).
OH masers are included within the boundaries of this map; there is nothing noticeably special about the spectra centered on the OH masers.

Figure 16 shows the spectra of four of the five BML regions from Table 2 in the CO(2 → 1), CS(2 → 1), and CS(3 → 2) lines. The CO(2 → 1) lines are characterized by a moderately broad (20–30 km s⁻¹) component with narrow absorption lines biting notches out of the broad line profile for W28 BML2 and BML4. Table 2 shows the brightnesses and velocities of the various lines, determined using Gaussian fits. For BML2 and BML4, the CO(2 → 1) absorption notches are listed separately as negative Gaussians. For BML3, the line profiles were best fitted with a sum of broad and narrow Gaussians; this does not mean that there are two separate components, as the combination of foreground absorption and a non-Gaussian profile can give the impression of two components even when there is only a single emission component. Recall that both W28 and W44 are located far from the Sun and near the Galactic plane, so there are several clouds between the remnants and the Sun. For BML5, the CS(3 → 2) line is weak, and the wings are probably lost in the noise.

The millimeter-wave line ratios for W28 BML1–BML5 are generally similar to each other: CS(2 → 1)/CO(2 → 1) ∼ 0.04 and CS(3 → 2)/CS(2 → 1) ∼ 1.0. In 3C 391 BML1, the CS lines are weaker, relative to CO(2 → 1), by a factor of 2, but the ratio CS(3 → 2)/CS(2 → 1) is similar, suggesting similar excitation conditions of $T_k$ ∼ 100 K and $n(H_2)$ ∼ $10^5$ cm⁻³ (Reach & Rho 1996). The abundances of CS and HCO⁺ are similar to those found in 3C 391 and IC 443 (Ziurys et al. 1989) to within a factor of 3.

The SiO(2 → 1) line was detected toward W28 BML1. Figure 17 shows the spectrum, and Table 2 shows the line fit. While the emission is weak, the SiO line profile is similar to other molecular transitions observed toward the same position. Of the other positions observed in this line, neither W44 OH B nor W44 OH F were detected, with $T_A < 0.12$ K. Because Si is locked in grains in quiescent interstellar gas, the presence of Si in the gas phase indicates either grain destruction or advanced grain-surface chemistry. Ziurys et al. (1989) detected SiO toward IC 443 and argued that the gas responsible for it has strongly enhanced SiO abundance, 100 times the upper limits of SiO abundance in dark clouds. Schilke et al. (1997) modeled the production of SiO in shocks and showed that the abundance is strongly enhanced by Si liberated from the shocked grain mantles and reacting with other molecules in the postshock gas.

To get the SiO line brightness we observed requires that the shocks be faster than 20 km s⁻¹, consistent with the observed line width of 21 km s⁻¹ (representing a lower limit to the shock velocity). Gas-phase Si was also detected in the far-infrared spectra of both W28 and W44, through the 34.8 μm fine-structure line of Si⁺ (Reach & Rho 2000).

4.2. Near-Infrared Results for W28

Let us now inspect the near-infrared image. The eastern portion of W28 (Fig. 18) contains the brightest H₂ emission we observed in either remnant. There are large-scale H₂ arc complexes, one in the southeast and one in the northeast. The southeast large-scale arc is a very bright spur running from the easternmost portion of the arc toward the northwest. The bright bars contain the BML regions W28 BML2 (brighter bar running diagonally southeast-northwest) and W28 BML4 (upper bar running more north-south); these bright, broad, linear features have an average surface brightness of $10^{-3}$ ergs cm⁻² s⁻¹ sr⁻¹.

Fainter H₂ arcs are distributed throughout the region, generally along and parallel to the radio ridge, which comprises a north-south bar that turns roughly at a right angle into an east-west part at the location of the northeastern H₂ arc. The northeastern and southeastern H₂ arcs are connected by fainter emission; as a whole this H₂ ridge runs almost exactly parallel to the ridge of CO wing emission in Figure 13g. The CO wing region W28 BML1 is located just west of a relatively bright H₂ filament in the northeastern arc; this filament is probably due to a single, bright, edge-on shock propagating into a dense molecular core.

The northern radio ridge, which runs east-west across the region covered by Figure 18 about one-third of the way from the top, contains the ridge of shocked CO(3 → 2) emission that was detected by Arikawa et al. (1999). There are some thin H₂ filaments that probably represent edge-on shocks. A pair of bright, nearly parallel filaments bracket a bright star near the
5. DISCUSSION

5.1. Correlation between the Shocked CO and H$_2$

The clumpy H$_2$ emission is spatially associated with the broad-line CO emission. Examples of this are in the southern part of W44, where the bright elliptical region of H$_2$ emission (Fig. 9) corresponds to the broad-line CO-emitting region near W44 OH B (Fig. 7). In addition, the bright H$_2$ emission in W28 exists in a region of broad CO lines; Figure 19 shows the CO overlaid on the H$_2$ image. The correspondence between H$_2$ and CO is not perfect, but the overall locations of the CO and H$_2$ are similar, and some features agree in detail. In particular, the bright CO bars in the southern portion of the image are both associated with H$_2$. Individual H$_2$ filaments are narrow ($\sim 1''$), so they are highly diluted in the CO beam ($30''$) and may be detected with better angular resolution or sensitivity.

A good correspondence between H$_2$ and broad CO was seen for IC 443 (Burton et al. 1988; Rho et al. 2001). Such correspondence was also seen in 3C 391, where the H$_2$ has broken into clumps that are likely preexisting dense cores in the parent molecular cloud (Reach & Rho 2000). Such condensations are expected in star-forming clouds such as the parent clouds of W28 and W44. Since the progenitors of W28 and W44 were massive stars, forming rapidly and existing as stars briefly, it appears there is continuing formation of lower mass stars from the same clouds, in accordance with the initial mass function (Scalo 1986). The blast waves from the W28 and W44 progenitors are propagating into these environments, which span a range of densities. The volume density inferred from the CO excitation discussed above, and from the detection of far-infrared H$_2$O, OH, and high-J CO lines (Reach & Rho 1998), is $n_c > 10^5$ cm$^{-3}$. Prestellar cores have extensive regions with densities of $\sim 10^5$ cm$^{-3}$ for timescales of $\sim 10^5$ yr (André et al. 2000). Shocks into these regions are nondissociative, and the H$_2$ emission arises from collisionally heated molecules behind the shock (Draine et al. 1983).

5.2. Physical Properties of the Shocked CO

The CO observations clearly differentiate between the shocked and unshocked gas. In addition to the broad-line profile, the
brightness ratios among the various spectral lines are different in the shocked gas as compared to the ambient gas. This is because the shocked gas is warmer (and often denser) than the unshocked gas, so that the relative brightness of the shocked gas is higher in CO(2 → 1) than in CO(1 → 0). Figure 20 illustrates this clearly. The narrow component is present in both spectral lines, with identical width. The brightness ratio illustrates this clearly. The narrow component is present in both unshocked gas, so that the relative brightness of the shocked gas is warmer (and often denser) than the ambient gas. The brightness ratios among the various spectral lines are different in the shocked gas as compared to the ambient gas. This is because the shocked gas is warmer (and often denser) than the unshocked gas, so that the relative brightness of the shocked gas is higher in CO(2 → 1) than in CO(1 → 0). Figure 20 illustrates this clearly. The narrow component is present in both spectral lines, with identical width. The brightness ratio \( \frac{R_{21}}{R_{07}} \) was observed for clouds in the Galactic center region, and 0.77 and 0.66 were observed for two giant molecular clouds in Orion, consistent with cold, optically thick gas, for example, \( T \sim 10 \) K and \( n \sim 10^3 \) cm\(^{-3}\) (Oka et al. 1996; Sakamoto et al. 1994).

The broad component is much fainter in CO(1 → 0) than in CO(2 → 1): \( R_{21} = 3.5 \pm 0.9 \), using the line integral over \( -20 \) to \( +65 \) km s\(^{-1}\) after subtracting the narrow component. The line ratio \( R_{21} \) for the shocked gas is much higher than that of the ambient molecular gas, as a result of a combination of heating and compression. A similarly high \( R_{21} \) was seen for the shocked gas in HB 21 (Koo et al. 2001) and IC 443 (Seta et al. 1998). That the line ratios are different is not surprising, if the broad line arises from molecules surviving a C-type shock while the narrow line is mostly ambient, unshocked gas. The utility of CO(2 → 1)/CO(1 → 0) as a tracer of shocked gas has also been discussed by Seta et al. (1998). The actual line ratio could be even higher in the shocked gas, if there is significant structure on angular scales smaller than the beam (which is likely, given the fine-scale structure of the shocked H\(_2\) images), so it is clear that there is a dramatic difference between the properties of the shocked and ambient gas.

We can constrain the physical properties of the broad-line-emitting gas using \( R_{21} \) and the isotopic brightness ratio \( R_{13/12} \). From Figure 5 the upper limit to the brightness of \( ^{13}\text{CO}(1 → 0) \) is 2\% of the brightness of CO(2 → 1), which converts, using \( R_{21} = 3.5 \), to a brightness ratio \( R_{13/12} < 0.07 \). Assuming an isotopic ratio of \( ^{13}\text{CO}/^{12}\text{CO} = 50 \) (Wilson & Rood 1994), the upper limit to the optical depth is \( \tau[^{13}\text{CO}(1 → 0)] < 3 \). Using the optically thin limit and balancing collisions and radiative transitions for the lowest several levels of CO, we find that the temperature of the shocked CO is \( \sim 100 \) K, independent of density, and a lower limit to the density is \( n(\text{H}_2) > 4 \times 10^3 \) cm\(^{-3}\).

An independent estimate of the properties can be obtained from the CS observations. For lines of sight with detected

| R.A. (J2000.0) | Decl. (J2000.0) | \( \frac{\int T_{mb} \, dv}{\nu} \) (K km s\(^{-1}\)) | \( \langle V \rangle \) (km s\(^{-1}\)) | \( \Delta V \) (km s\(^{-1}\)) | Line |
|---------------|----------------|--------------------------------|-----------------|-----------------|------|
| W28 BML1 | | 18 01 52.0............ | −23 18 47 | 466 | 11.7 | 21.3 | CO (2 → 1) |
| | | | | | | 19 | 4.3 | 18.2 | CS (2 → 1) |
| | | | | | | 33 | 3.6 | 28.8 | HCO\(^+\) (1 → 0) |
| | | | | | | 3.2 | 9.6 | 21.9 | SiO (2 → 1) |
| W28 BML2 | | 18 01 37.4............ | −23 25 44 | 970 | 7.1 | 18.9 | CO (2 → 1) |
| | | | | | | | 21 | 8.0 | 1.5 | CO (2 → 1) absorption |
| | | | | | | | 36 | 6.6 | 12.1 | CS (2 → 1) |
| | | | | | | | 37 | 6.6 | 15.6 | CS (3 → 2) |
| W28 BML3 | | 18 01 44.1............ | −23 24 24 | 422 | 9.1 | 17.1 | CO (2 → 1) broad |
| | | | | | | | 100 | 5.8 | 3.8 | CO (2 → 1) narrow |
| | | | | | | | 14 | 7.5 | 8.9 | CS (2 → 1) broad |
| | | | | | | | 8 | 6.1 | 2.4 | CS (2 → 1) narrow |
| | | | | | | | 14 | 7.5 | 8.9 | CS (3 → 2) broad |
| | | | | | | | 8 | 6.1 | 2.4 | CS (3 → 2) narrow |
| W28 BML4 | | 18 01 39.5............ | −23 25 04 | 1090 | 7.6 | 24.1 | CO (2 → 1) |
| | | | | | | | | 29 | 7.6 | 1.2 | CO (2 → 1) absorption |
| | | | | | | | | 43 | 7.6 | 15.6 | CS (2 → 1) |
| | | | | | | | | 41 | 7.3 | 15.0 | CS (3 → 2) |
| W28 BML5 | | 18 01 38.8............ | −23 29 03 | 840 | 2.4 | 30.4 | CO (2 → 1) |
| | | | | | | | | 25 | 5.5 | 29.2 | CS (2 → 1) |
| | | | | | | | | 17 | 5.4 | 11.1 | CS (3 → 2) |

Note.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.
of regions where OH masers lie along H$_2$ filaments are seen in the northeast portion and southern portion (Fig. 24) of W44 as well. The spatial alignments are too detailed to be coincidence. Counter-examples of similar filaments with no OH masers, or OH masers not located on bright H$_2$ filaments, are present throughout both remnants. Wherever there are OH masers, however, there is H$_2$ emission. Thus, it appears that OH masers are a very nonlinear tracer of shocked molecular gas. The presence of OH masers clearly indicates molecular shocks, but a lack of OH masers is not informative.

5.4. Shock Thickness

The H$_2$ images of W28 and W44 reveal bright, complex regions, as well as a network of fainter, narrow filaments. Figure 21 shows an example of a region with many narrow filaments. The individual shock fronts in W28 and W44 are barely resolved in the near-infrared H$_2$ images, with angular widths $\lesssim 0\circ.7$. If they are interpreted as edge-on shock fronts, then we are observing shock fronts with thicknesses of $\lesssim 12 \times 10^{16}$ cm. This is really an upper limit, because the narrowest shocks are unresolved at the limit of atmospheric seeing, and all these shocks have some inclination with respect to the line of sight. In what follows, we compare the shock thickness with theoretical models for nondissociative and dissociative shocks.

The observed widths agree with the predictions for nondissociative shocks with properties as were invoked above to explain other properties of the gas (CO and CS line ratios). From equation (3.12) of Draine & McKee (1993), using a preshock magnetic field strength of $b_{n1/2} \mu$G where $n$ is the preshock gas density in cm$^{-3}$ and $b$ is a dimensionless field strength of order unity, the shock thickness

$$L \sim 1.3 \times 10^{16} b \left(10^{-4}/x\right) (10^2/n) \text{ cm},$$

where $x = n_i/n$ and $n_i$ is the ion density. For preshock gas densities between $n = 10^2$ and $10^4$ cm$^{-3}$ and corresponding ionization fractions between $x = 10^{-4}$ and $10^{-7}$, respectively, the shock thickness is in the range $(1-10) \times 10^{16}$ cm. Draine et al. (1983), in Figures 1 and 2 of their paper, predict the structures of 25 km s$^{-1}$ shocks into gas with preshock H-nucleon densities of $10^2$ and $10^4$ cm$^{-3}$. The widths of the regions where H$_2$ would be heated, but not converted into more complex molecules such as H$_2$O, are smaller than the total shock thickness estimated by the equations above: reading from their figures, the H$_2$ emission regions are $\sim 1 \times 10^{16}$ cm. The observed widths of the shock fronts are consistent with nondissociative shocks into gas with densities of order $10^4$ cm$^{-3}$. Shocks into gas with a preshock density of $10^6$ cm$^{-3}$ (if they are steady shocks, which may not occur on the timescales of the remnants we are observing) are predicted to be wider than observed, and Figure 3 of Draine et al. (1983) shows that most of the cooling will come from coolants other than H$_2$.

Faster, dissociative shocks can also produce H$_2$ emission from molecules re-forming behind the shock. Hollenbach & McKee (1989) calculated the width of the H$_2$ re-formation region to be (their eq. [3.4])

$$5 \times 10^{17} b(100/n) \left(1 + 100 e^{-6 (10^6/n)^{1/2}}\right) \text{ cm},$$

for a shock speed of 100 km s$^{-1}$, as was inferred from the width of the O i 63 $\mu$m emission line (Reach & Rho 2000). The observed shock thickness can be produced if the density $n \sim 10^3$ cm$^{-3}$. Thus, based only on the observed thickness, there
Fig. 15.—Grid of CO(2–1) spectra toward BML regions in W28, with a spacing of 200". Within this 10 × 13 grid, W28 BML4 is in column (7), row (8) (counting from the lower left), W28 BML3 is in the upper left of this grid. OH 1720 MHz masers are OH C2 (col. [10], row [12]), OH D2 (col. [5], row [5]), and OH D3 (col. [5], row [4]) (Claussen et al. 1997).
Fig. 16.—Spectra of (a) W28 BML2, (b) W28 BML3, (c) W28 BML4, and (d) W28 BML5 in the CO(2 → 1) (top), CS(2 → 1) (middle), and CS(3 → 2) (bottom) lines.

Fig. 17.—Spectra of SiO emission from W28 BML1, taken with the IRAM 30 m. This spectrum combines 30 minutes of on-source integration. The spectra of three other molecules toward the same position (and smoothed to the same angular resolution) are shown for comparison.

Fig. 18.—H$_2$ 2.12 µm image of the eastern portion of W28.
are two types of shock that can produce structures with the
thickness observed: nondissociative shocks into gas with den-
sity $k_{104} \, \text{cm}^{-3}$ and dissociative shocks into gas with density
$\rho_{24} \, \text{cm}^{-3}$.

5.5. Relation between Molecular and Ionic Shocks

Portions of the remnants were observed in the Fe $\, 1.644 \, \mu \text{m}$
filter. While the H$_2$ emission is bright and extended, with in-
tricate filaments as well as bright blobs, the Fe emission is
weak and relatively diffuse. Figure 22 shows the Fe image of
the southern portion of W44, revealing two diagonal filaments,
qualitatively similar to the H$_2$ image (Fig. 9) but with the Fe
filaments much more diffuse and shifted north of the H$_2$
filaments. The separation of the Fe and H$_2$ emission is not par-
ticularly surprising, considering that the physical conditions of
the shocks traced by these lines are very different. However, the
Hollenbach & McKee (1989) and tentatively observed in one remnant by Koo & Moon (1997). However, the H$_2$ emission in this image of W44 is located farther from the remnant center than the Fe $\text{ii}$-emitting region, whereas re-formed molecules should be behind the shock. The observed separation between the molecular and ionic shocks is $2 \times 10^{18}$ cm, which is much larger than the expected size of the molecular re-formation region behind a fast shock: for $n_0 = 10^3$ cm$^{-3}$ and $v_s = 100$ km s$^{-1}$, $z_{1/2} \approx 10^{15}$ cm (Hollenbach & McKee 1989). The Fe $\text{ii}$ traces a combination of grain destruction (to get Fe in the gas phase) and hot and dense regions (to excite the upper energy levels). It is unlikely that the Fe $\text{ii}$-emitting region could end up farther behind the shock than the H$_2$ emission.

Therefore, we interpret the Fe $\text{ii}$ and H$_2$ filaments as tracing independent shocks: the Fe $\text{ii}$ traces fast, grain-destroying shocks into $n < 10^3$ cm$^{-3}$ gas, while the H$_2$ traces denser shocks. The reason for their rough correspondence and occasional parallel alignment on the sky probably reflects the preshock structure of the molecular cloud. When approaching a dense portion of the molecular cloud, the blast wave first encounters the less dense material at its surface, yielding the ionic shocks. Slower shocks then begin propagating into the denser material, yielding the molecular shocks.

5.6. Shock Brightness

The H$_2$ ($1 \rightarrow 0$) $S(1)$ line brightness of the individual, filamentary shock fronts in Figure 21 is about $5 \times 10^{-5}$ ergs s$^{-1}$ cm$^{-2}$ sr$^{-1}$. Brighter features, such as the bright clump in Figure 9, range up to $2 \times 10^{-4}$ ergs s$^{-1}$ cm$^{-2}$ sr$^{-1}$. Let us compare these values with those predicted by shock models consistent with other observed properties. The predicted face-on brightness of nondissociative shock fronts into gas with $n = 10^4$ cm$^{-3}$ and $V_s = 25$ km s$^{-1}$ is $\sim 3 \times 10^{-3}$ ergs s$^{-1}$ cm$^{-2}$ sr$^{-1}$ (Draine et al. 1983), and the predicted face-on brightness of dissociative J-shocks into gas with $n = 10^3$ cm$^{-3}$ and $V_s = 100$ km s$^{-1}$ is $\sim 2 \times 10^{-5}$ ergs s$^{-1}$ cm$^{-2}$ sr$^{-1}$ (Hollenbach & McKee 1989). Both of these predictions are comparable to, but a factor of 2–3 fainter than, the brightness of the individual filamentary shock fronts. The theoretical models are for face-on shocks, which are fainter than edge-on shocks. It is quite plausible for there to be a factor of 2–3 geometric correction between face-on (theoretical) and more nearly edge-on (observed) geometries. It is a rather remarkable coincidence that both the thickness and brightness of the near-infrared H$_2$ emission, from two very different types of shocks, are so similar.

There is a significant difference in the physical properties of H$_2$ behind the different shocks. Behind a nondissociative, C-type shock, the H$_2$ molecules are heated without being dissociated; there must exist a critical type of shock that can just barely dissociate H$_2$ and that will yield the highest possible excitation. The neutral gas temperature behind such shocks reaches 10$^3$ K and then cools rapidly, leading to bright emission from the $S(3)$ and $S(5)$ pure rotational lines (Draine et al. 1983). In contrast, behind a faster shock, the H$_2$ molecules are destroyed and the H ionized; the molecules re-form $\sim 10^{17}$ cm behind the shock, where the temperature is 10$^{2.5}$ K and lower. The cooling is somewhat slower because of the lower density, leading to bright emission from the $S(7)$ and $S(9)$ pure rotational lines (Hollenbach & McKee 1989). Let us now take models consistent with the observed near-infrared $1 \rightarrow 0$ $S(1)$ line brightness and consider the Infrared Space Observatory data on the pure rotational lines. For one line of sight in each remnant, near W28 OH F and W44 OH E, we detected the $S(3)$ and $S(9)$ lines in the $14'' \times 20''$ spectrometer aperture (Reach & Rho...
Most attention has been focused on young supernova remnants, in which the near-infrared H$_2$ emission and broad CO emission trace shocks into dense gas ($n_\text{H}_2 > 10^4$ cm$^{-3}$). The ratios $S(9)/S(3)$ are 0.1 and 0.5 for W28 OH F and W44 OH E, respectively, with less than 10% uncertainties. The predicted line ratios are $S(9)/S(3) = 10$ for the dissociative shock and $S(9)/S(3) = 0.02$ for the nondissociative shock. The observed line ratio is inconsistent with both shock models, so we infer that there must be different types of shock producing different lines. Using the theoretically predicted ratios of the $S(3)$ and $S(9)$ lines, the $S(3)$ line arises almost exclusively from the nondissociative shock ($\approx 94\%$), while the $S(9)$ line arises largely from the dissociative shock ($\approx 83\%$). Thus, both types of shock are expected to contribute to the near-infrared H$_2$ emission with comparable brightness averaged over large beams.

To distinguish between the dissociative and nondissociative shocks, we must turn to evidence other than the shock width and brightness. 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 ($\approx 2$ pc). If the filamentary H$_2$ emission were from a shock front propagating into a coherent three-dimensional region with this size and density, the preshock gas would have a mass $\gg 10^4 M_\odot$ and would have been easily visible in the millimeter-wave lines that trace such gas. In fact, the CS(2–1) spectra do not show such large-scale dense material, revealing instead only relatively isolated cores with much smaller size. The distribution of preshock molecular gas is complicated, and the new images of shock fronts propagating into giant molecular clouds presented in this paper deserve more complicated theoretical models to elucidate both the shock physics and preshock gas distribution.

### 5.7. Molecular Shocks and Cosmic Rays

Supernova remnants are the most plausible source for Galactic cosmic rays (Draine & McKee 1993; Jones & Ellison 1991). Most attention has been focused on young supernova remnants, in which the shocks are strong enough to accelerate thermal electrons to relativistic energies. W28 and W44 are very bright radio continuum sources (Clark & Caswell 1976); they are the sixth and seventh brightest supernova remnants out of 232 remnants in the Green (2001) catalog. The synchrotron radiation could be bright for several reasons: the strength of the magnetic field in the dense material with which the blast waves are interacting, local acceleration of particles to high energies, reacceleration of existing high-energy particles, or some combination of these effects. Particle acceleration (or reacceleration) will depend on the physical conditions of the preshock gas and the strength of the shock.

If all the present-day shocks into different regions are being driven by the same ram pressure, then we can discern which types of preshock gas are the most likely origin for particle acceleration or reacceleration by comparing images that trace the various types of shock to the radio image. For young remnants, the radio and X-ray images sometimes show very close correspondence, for example, the images of Tycho compared by Blandford & Cowie (1982) or the near-infrared synchrotron, radio, and X-ray images of Cas A compared by Rho et al. (2003), so the cosmic-ray acceleration is associated with the main blast wave. But for mixed-morphology remnants such as W28 and W44, whose defining characteristic is the contrasting X-ray and radio morphology, we must look to shocks that do not emit copious X-rays to find the source of cosmic-ray acceleration.

First, let us compare the H$_\alpha$ and radio images. We assume that the near-infrared H$_2$ emission and broad CO emission trace shocks into dense gas ($n_\text{H}_2 \sim 5$ cm$^{-3}$), and the H$_\alpha$ image traces shocks into lower density gas ($n_\text{H}_2 < 10^3$ cm$^{-3}$). Figure 23 shows that the radio image is quite different from H$_\alpha$ for W28, with the radio shell surrounding the centrally filled H$_\alpha$ emission. This morphology was already noted by Van den Bergh et al. (1973). Some faint H$_\alpha$ emission is associated with the outer radio shell, for example, along the northernmost radio arc and the northwestern portion of the remnant (Dubner et al. 2000). But the vast majority of the H$_\alpha$ emission arises from the interior of the remnant, where the radio emission is very weak. In particular, the brightest radio emission arises from a very bright bar that runs north-south and forms the eastern boundary of the remnant. The H$_\alpha$ emission fills the interior of the remnant and ends abruptly at the radio bar. The second brightest radio feature is a bar that runs east-west in the northern part of the remnant. The bright H$_\alpha$ emission in the interior again terminates at this radio bar as well. The third brightest radio feature is a thin arc of faint emission that forms the far northern boundary of the remnant; this is where some faint H$_\alpha$ emission appears associated with the radio emission. Thus, it appears that, for the most part, the inner boundary of the radio shell delineates the outer boundary of the H$_\alpha$-emitting region. The morphologies of the radio and H$_\alpha$-emitting regions are different: while the radio can be described as a set of large, coherent arcs running along the edge of the remnant, the H$_\alpha$ emission is highly structured, with many very thin filaments, some of which run orthogonal to the radio arcs. The difference in fine structure is difficult to assess with the present data, however, because the angular resolution of the radio data is much lower than that of the H$_\alpha$. Similar results obtain for W44, although the H$_\alpha$ emission is weaker. Rho et al. (1994) showed that the H$_\alpha$ emission is interior to the radio shell and has a different morphology. Giacani et al. (1997) showed that there are some portions of W44 where the H$_\alpha$ and [S II] appear to follow each other and the radio, although there is also optical emission from regions with no corresponding radio emission. The situation for both W28 and W44 is that some regions have corresponding H$_\alpha$ and radio emission, but for the most part (and especially in the interior of the remnant), the radio and optical images are very different.

Next, let us compare the H$_2$ and radio images. Figure 24 shows radio contours overlaid on the H$_2$ image of the southern portion of W44. Both images are dominated by two diagonal filaments running southeast-northwest across the field. The orientation of the filaments matches remarkably well in these two images of disparate emission mechanisms. The radio emission from the southernmost of the two bright filaments overlays the H$_2$ filament very closely. Even the relatively faint radio and H$_2$ features have very good correspondence, throughout this image.

The brightest patch of H$_2$ emission, which is just south of the northern filament in Figure 24 and contains the W44 OH B maser complex, has a faint radio counterpart of about 1.5 mJy beam$^{-1}$ brightness. The radio/H$_2$ ratio is 3 times less in the H$_2$ clump than in the H$_2$ filaments. The shocks into the highest density gas, traced by the “clumpy” type of H$_2$ emission (as opposed to the long, thin filaments), OH masers, and wide CO lines, apparently have a lower synchrotron emissivity than the filaments.

For W28, a similar correspondence is found between H$_2$ and radio emission, although the angular resolution of the radio image is much worse. The bright H$_2$ emission in the southeast portion of Figure 18 is precisely where the radio emission in the remnant is brightest in its north-south bar. The shocked CO emission was shown to be well correlated with the radio image by Arikawa et al. (1999) and Dubner et al. (2000).
Because the radio and shocked molecular filaments are well correlated, we suggest that the bright radio emission from W28 and W44 is due to interaction between the remnant and molecular gas. Such an association is somewhat surprising, because it would seem that the fastest shocks would be most closely associated with energetic particle acceleration. However, strong magnetic fields in dense gas and the presence of stronger shocks into the lower density gas combine to provide the particle acceleration and synchrotron enhancement, respectively. Bykov et al. (2000) have addressed this issue theoretically. The present-day shocks in W28 and W44 may not be strong enough to be primary accelerators of cosmic rays, although fast shock fronts are capable of accelerating thermal electrons to relativistic energies (Jones & Ellison 1991). What we observe as enhanced radio emission are relativistic particles that emit bright synchrotron radiation as they spiral around the strong magnetic field in the compressed regions behind the molecular shocks. This mechanism was proposed by Blandford & Cowie (1982). For a remnant of given explosion energy and present size, the radio surface brightness depends primarily on the filling factor \( f \) of the dense material behind the shock: \( \Sigma \propto B^{-0.3}f \), where \( B \) is the magnetic field in the dense gas. The radio map is therefore predicted to trace the dense gas, as is indeed observed in Figure 24. Quantitatively, the radio brightness of W44 ranges from 3 to 10 MJy sr\(^{-1}\) (where 1 MJy = \( 10^{-17} \) ergs s\(^{-1}\) cm\(^{-2}\) Hz\(^{-1}\)) at 1420 MHz. The observed brightness is somewhat higher than the model predictions, even for a high filling factor of dense gas; this is not surprising, because the model assumes a low filling factor and neglects the effect of the high density on the remnant evolution, which becomes important at higher filling factors. Thus, our new observations appear to confirm the concept proposed by Blandford & Cowie (1982).

Based on far-infrared and millimeter-wave spectroscopy, we have suggested that there are three types of gas that produce the main observable features of supernova remnants interacting with molecular clouds (Reach & Rho 2000). Table 3 describes the physical properties of these three types of gas. The three types \( i \) of gas, with density \( n_i \), shock velocity \( V_i \), and filling factor \( f_i \), will contribute to the synchrotron emission proportionally to \( n_i^{1.75}V_i^2f_i \), assuming the magnetic field \( B_i \propto n_i^{0.5} \). The kinetic energy in their shocks will be proportional to \( P_{\text{ram},i}f_i \propto n_iV_i^2f_i \). The filling factors in Table 3 are very rough approximations based on the fraction of remnant surface that is traced by each phase. The ram pressure of shocks into the different phases is similar but not equal: the observed properties of the denser shocks seem to require higher ram pressure (Reach & Rho 1996). This

![Figure 23](image_url)
The radio emission arises from the intermediate-density molecular phase, in agreement with our finding that the H$_2$ and radio images are associated. Phase $M$ dominates the mass, although phase $A$ contains the most kinetic energy.

There is another possible source of energetic particles, at least for W44: the pulsar PSR 1853+01. The pulsar is located just north of Figure 24, and the distance from the pulsar to the northern radio filament is only $\sim 10^{18}$ cm. The radio filaments in W44 seem to converge in the southwest portion of the remnant, and we speculate that energetic particles could originate from the pulsar wind and then spiral along the filaments of enhanced magnetic field. De Jager & Mastichiadis (1997) also proposed that the pulsar supplies the energetic particles, based on an interpretation of the radio to $\gamma$-ray spectrum.

5.8. Implications for the Structure of Molecular Clouds

We mentioned in §1 that theoretical models (Cox et al. 1999; Chevalier 1999) for molecular supernova remnants explain most observable properties as shocks into gas with a density of $5$ cm$^{-3}$. These models are well grounded in observational data: in particular, H$\i$ 21 cm observations indicate neutral hydrogen shells containing $\sim 10^3 M_\odot$ of material, suggesting preshock densities of $\sim 2$–$5$ cm$^{-3}$ for W28 (Velázquez et al. 2002) and W44 (Koo & Heiles 1995). From our millimeter-wave and infrared observations, we have inferred shocks into gas with
Molecular clouds comprise regions with a wide range of densities, from dense, star-forming cores with $n > 10^4$ cm$^{-3}$ to CO-emitting regions with $n > 10^2$ cm$^{-3}$ and, possibly lower if there is interclump gas. Detailed observations of molecular clouds have shown that CO emission is from regions with volume density $n_M$ much higher than the path length–averaged density $\langle n \rangle \equiv N/L$. For a giant molecular cloud such as the ones near W44 and W28, $N \sim 2 \times 10^{21}$ cm$^{-2}$ and $L \sim 100$ pc, so $\langle n \rangle \sim 10^2$ cm$^{-3}$. A detailed study of the Rosette molecular cloud reveals that the CO emission arises from clumps that occupy only $8\%$ of the cloud volume; the remainder of the cloud is filled with diffuse atomic gas with a mean density $n_A \sim 4$ cm$^{-3}$ (Williams et al. 1995). In a recent study of $\text{H}^+$ absorption toward a large sample of dark clouds, Li & Goldsmith (2003) showed pervasive atomic gas within molecular clouds, with a volume density $n(\text{H}^+) \sim 4$ cm$^{-3}$. They interpreted the $\text{H}^+$ as the product of cosmic-ray destruction of $\text{H}_2$ in dark clouds; since the $\text{H}^+$ volume density is predicted to be independent of the $\text{H}_2$ density, the $\text{H}^+$ can be thought of as an interclump medium in a clumpy cloud. There is increasing evidence that the bulk of the mass of molecular clouds resides in clumps that fill only a small fraction of the cloud. An IRAM key project demonstrated that CO emission arises from cells that do not fill the volume of the cloud, having densities of $10^3$–$10^5$ cm$^{-3}$ and sizes of order 200 AU (Falgarone et al. 1998). Multilevel excitation studies show that even the CO($4 \rightarrow 3$) line is bright enough that the fourth rotational level is excited; the inferred volume density $n_M \sim 10^{4.5}$ cm$^{-3}$ (Ingalls et al. 2000).

6. CONCLUSIONS

We have used supernova blast waves as a means of illuminating cloud structure. Radiative shocks into gas of different densities have different cooling mechanisms, allowing us to separate shocks into dense cores, moderate-density molecular gas, and interclump atomic gas. Giant molecular clouds are pervaded by interclump gas with density of $\sim 5$ cm$^{-3}$, with moderate-density CO-emitting portions occupying $\sim 10\%$, and denser gas occupying a yet smaller volume.

One of the defining characteristics of supernova remnants in the mixed-morphology class to which W28 and W44 belong is their centrally condensed, thermal X-ray emission (Rho & Petre 1998). Two competing theoretical explanations for the presence of such a large amount of interior X-ray–emitting gas involve evaporating clumps inside the remnant (White & Long 1991) and thermal conduction behind radiative shocks (Cox et al. 1999). We now suspect that both mechanisms are operating. The thermal conduction model explains some interior X-rays, assuming shocks into interclump gas with a density of 5 cm$^{-3}$, but this model does not produce a central column density peak with the very flat temperature profile required to match the X-ray observations. The combination of the radiative shock into the interclump gas and evaporating material from the dense clumps that survive the shock may work in combination to produce the X-ray--emitting material. A reservoir of dense material that can survive the initial blast wave is clearly present: it manifests itself through BML regions, bright $\text{H}_2$ clumps, and OH masers. The shocks into these clumps are much slower than the shock into the interclump gas, which leaves the clumps behind to evaporate in the interior. The variegated appearances of these two supernova remnants interacting with molecular clouds owe to the wide range of densities already present in the clouds, with fast shocks producing X-ray, $\text{H}_\alpha$, and $\text{Fe}$ ii emission, slower shocks into moderate-density gas producing filamentary $\text{H}_2$ and radio emission, and slower yet shocks into dense cores producing CO, CS, and HCO$^+$ emission.
This work is based on observations obtained at the Hale Telescope, Palomar Observatory, as part of a continuing collaboration between the California Institute of Technology, the NASA Jet Propulsion Laboratory, and Cornell University. We are pleased to acknowledge the assistance of Naman Bhatt, who worked with us for a summer on this project. This publication makes use of data products from the Two Micron All Sky Survey, which is a joint project of the University of Massachusetts and the Infrared Processing and Analysis Center, California Institute of Technology, funded by NASA and the National Science Foundation. Observations with the 12 m telescope were made while that telescope was being operated by the NRAO. The NRAO is a facility of the National Science Foundation, operated under cooperative agreement by Associated Universities, Inc. The research described in this paper was carried out at the California Institute of Technology under a contract with NASA.

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