MOLECULAR HYDROGEN OUTFLOWS IN W51

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ABSTRACT

We present the results of a deep search for the molecular hydrogen shock fronts associated with young stellar outflows in the giant molecular cloud and massive star-forming region W51. A total of 14 outflows were identified by comparing images in the H and K bands and in a narrowband filter centered on the H$_2$ 1–0 $S(1)$ line at 2.122 $\mu$m. A few of the newly discovered outflows were subsequently imaged at higher spatial resolution in the $S(1)$ filter; one outflow was also imaged in the 1.644 $\mu$m emission line of [Fe II]. For two of the outflows, high-resolution echelle spectroscopy in the H$_2$ 1–0 $S(1)$ line was obtained using NIRSPEC at Keck. For one outflow additional high-resolution spectra were obtained in the [Fe II] line and in Br$\gamma$. The largest and best-studied outflow shock front shows a remarkably broad [Fe II] line, an unusual high-velocity component in Br$\gamma$, and comparably narrow line widths in the H$_2$ 1–0 $S(1)$ line. A scenario involving high-velocity shocks and UV excitation of preshock material is used to explain these spectra.

Subject headings: infrared: ISM — ISM: jets and outflows — ISM: lines and bands — ISM: molecules — stars: formation — stars: pre–main-sequence

1. INTRODUCTION

The high-mass star-forming region W51 was discovered as a region of radio continuum emission by Westerhout (1958) and as a massive molecular cloud by Penzias, Jefferts, & Wilson (1971). It is one of the most luminous star-forming regions in our Galaxy and may be the closest analog to the extremely luminous star-forming regions found in many other galaxies (e.g., 30 Doradus in the LMC). W51 is far more luminous than the well-studied relatively nearby Orion star-forming region. The mass of the W51 complex has been estimated to be about $10^6 M_\odot$ (Carpenter & Sanders 1998), based on both virial mass estimates and $^{12}$CO intensities. Mass estimates of molecular clouds in a complex environment obviously depend on where the boundaries are set, and this estimate refers to a set of emission features of approximately spherical shape. W51 is in the top 1% of all galactic molecular clouds by size and the top 5%-10% by mass.

W51 lies in the plane of the Galaxy at the substantial distance of $7.0 \pm 1.5$ kpc measured by Genzel et al. (1981) through proper motion studies of the W51 Main H$_2$O maser. W51 is therefore heavily obscured by interstellar extinction ($A_V = 24 \pm 3$ mag, as measured by Goldader & Wynn-Williams [1994] on the basis of the color of the extended emission). W51 is about 14 times farther away than Orion, and the distance modulus is almost 6 mag larger than for Orion, in addition to an extra 2 mag of extinction in the K band, so that studies of W51 are necessarily limited to very bright objects and rather large extended features.

Numerous infrared sources were discovered in the radio continuum region W51. One of these, W51 IRS 2 (Wynn-Williams, Becklin, & Neugebauer 1974), corresponding to the radio-continuum region W51e (Martin 1972), is now known to be a young embedded star cluster larger than the Orion-Trapezium Cluster, as first suggested by Genzel et al. (1982). A detailed study of massive stars in W51e was done by Okumura et al. (2000). They identified four subgroups within W51, aligned roughly parallel to the Galactic plane, with average ages in those subgroups ranging from less than 1 Myr to 2.3 Myr. Past studies of W51 have largely focused on its global properties, e.g., the total luminosity and mass, and have traced the effects of star formation integrated over the lifetime of O stars by studying radio continuum or Br$\gamma$ emission.

This paper, by contrast, seeks to obtain a snapshot of star formation activity in the most recent past. Stars in their main accretion phase still have a substantial fraction of their final (zero-age main-sequence) mass residing in a circumstellar disk. They are therefore characterized by spectral energy distributions (SEDs) peaking at submillimeter wavelengths (Andrè, Ward-Thompson, & Barsony 1993) and are not directly detectable at near-infrared wavelengths. Fortunately, these Class 0 sources usually also have strong outflows that can be traced by the shock-excited emission of H$_2$ resulting from the interaction of the outflow with the ambient molecular cloud. Examples of successful searches for outflows using narrowband imaging in the H$_2$ 1–0 $S(1)$ line are, among many others, Hodapp & Ladd (1995), one of the earlier $S(1)$ imaging surveys, and Stanke, McCaughrean, & Zinnecker (1998), who conducted a survey of large areas in the Orion giant molecular cloud (GMC). Very strong outflow activity and shock-excited molecular hydrogen emission persists only through the Class 0 and early Class I phases, i.e., for less than $10^5$ yr. In contrast to the study of H II regions, H$_2$ outflows therefore trace contemporary lower mass star formation.

We will discuss the technical aspects of the observations in § 2. The results will be discussed in § 3, separated into discussions of the overall distribution of outflow sources in
§ 3.1 and of the morphology of individual outflows in § 3.2. Velocity-resolved spectroscopy of two outflows will be discussed in detail in §§ 3.3 and 3.4, and some results on the embedded IRS 2 cluster will be presented in § 3.5.

2. OBSERVATIONS AND DATA REDUCTION

The data for this study of outflows in W51 were obtained in three observing runs. The initial wide-field imaging data in H, H$_2$ 1–0 S(1) at 2.122 µm, and K were obtained in 1997 and formed the basis for identifying previously unknown outflows. Some of the brightest outflows discovered in this survey were subsequently imaged at higher spatial resolutions in S(1) and [Fe ii] in 2000 June. High-resolution spectroscopy of two outflows was obtained at Keck in 2000 May using NIRSPEC (McLean et al. 1998).

2.1. Wide-Field H-Band, S(1), and K-Band Images

Our search for emission-line objects in W51 is based on a wide-field mosaic obtained in the broadband H and K filters and in a narrowband filter centered on the H$_2$ 1–0 S(1) line at 2.122 µm. The data were obtained with the infrared camera QUIRC (Hodapp et al. 1996) on 1997 August 16–19 (UT) at the UH 2.2 m telescope f/10 focus. The pixel scale was 0″188 pixel$^{-1}$, resulting in a field of view of 193″ × 193″. To cover the large area of the W51 molecular cloud in a reasonable time, we used 10 s integration time in the H and K filters and 20 s in the molecular hydrogen S(1) narrowband filter. The imaging data were obtained in a 10 × 9 mosaicing pattern with 90″ spacing, so that every position on the sky is covered by at least four individual exposures. The total integration time for each point in the image is therefore 40 s in the broadband filters and 80 s in the S(1) narrowband filter.

The individual frames were flat-fielded using dome flats and known bad pixels were masked off. The individual reduced frames were assembled into the large mosaic by three separate images in the three filters were then combined into a false-color image, with H represented in blue, S(1) in green, and K in red. Regions of S(1) line emission stand out as greenish features in this color scheme. Visual inspection of potential shock-front features were checked on the individual H, S(1), and K mosaics, and false detections due to residual images, ghost images, or glare, as well as bad pixels or cosmic-ray hits were discarded.

The extended emission permeating much of the survey area has been shown by Okumura et al. (2001) to be dominated by Br$\gamma$ and He i emission but to also contain many emission lines of H$_2$, probably fluorescently excited by the UV field from the ionizing stars in the H II regions. In identifying shock-excited H$_2$ emission in the survey images, the distinction between shock-excited features and features excited by fluorescence in the stellar UV field can be based only on the strength of the H$_2$ emission, i.e., its contrast relative to the broadband images, and its morphology. Objects identified as shock fronts in our survey have a strong contrast to the broadband filters, indicating that their emission in the K band is dominated by H$_2$ emission. They either are marginally resolved small knots or clearly show the morphological features of bow shocks. In contrast, extended, rather diffuse features showing some H$_2$ emission, but not being dominated by it, that are also mostly located on the perimeter of the H II regions outlined in broadband K and the Br$\gamma$ image of Okumura et al. (2000), were not identified as potential stellar outflow shock fronts. These latter features are most likely excited by fluorescence in the UV radiation field generated by the ionizing stars in the H II regions, as first suggested by Okumura et al. (2001).

The extent of the survey area and the location of detected S(1) emission features fitting our search criteria is indicated in Figure 1, the K-band image produced in our survey. The individual emission knots, or systems of knots in cases of clearly related (bipolar) outflow features, are shown in Figure 2. For each object, the name follows the IAU conventions and includes the J2000 coordinates. Usually, the coordinates refer to the center of the extended emission region. In highly structured, irregular emission knots, the coordinates refer to the most prominent feature. For systems of emission features that morphologically appear to be part of one outflow, the coordinates refer to one of the features, and additional features are referred to by additional, self-explanatory designations (N, S, W, E, or C).

2.2. High-Resolution Emission-Line Imaging

To obtain images at higher spatial resolution of some of the likely outflow shock fronts discovered in the wide-field survey, tip-tilt-corrected images were obtained on 2000 June 16–19 (UT). The tip-tilt-corrected f/31 focus (Jim et al. 2000) of the University of Hawaii (UH) 2.2 m telescope was used, where the QUIRC infrared camera has a pixel scale of 0″062 pixel$^{-1}$ and a field of view of 63″ × 63″. Images were obtained in narrowband [Fe ii] 1.644 µm and H$_2$ 1–0 S(1) 2.122 µm filters, and the data were reduced in the same way as described above for the wide-field images. Under good seeing conditions, the tip-tilt-corrected images at 2.122 µm come close to the diffraction limit of the telescope and under more typical conditions, 0″3 FWHM is achieved.

2.3. Infrared Spectroscopy

High-resolution echelle spectroscopy of two of the outflow sources in W51 was obtained in the night of 2000 May 28 (UT) at the W. M. Keck Observatory, using the NIRSPEC (McLean et al. 1998) spectrograph. The weather this night was nonphotometric and unsuitable for flux calibration of the spectra.

The spectra were obtained with two grating and filter settings: The first setting was for observations in the K band, intended to cover several of the H$_2$ shock-excited emission lines but concentrating on the 1–0 S(1) line at $\lambda_{vac} = 2.1218334$ µm (Bragg, Smith, & Brault 1982). Observations in Br$\gamma$ were not part of the original observing plan, since this line is rarely excited in H$_2$ outflows. Fortunately, the Br$\gamma$ line at $\lambda_{vac} = 2.166167$ µm was also recorded in our K-band spectra, albeit near the edge of the detector array so that wavelength calibration was difficult. The other grating setting was for observations in the H band, primarily to

1 A compressed version of this false-color image can be downloaded from http://www.ifa.hawaii.edu/~hodapp/W51-sm-rgb.jpg.
observe the [Fe ii] line at $\lambda_{\text{vac}} = 1.64400 \, \mu\text{m}$ (Johansson 1978).

Since the objects are extended, sky spectra were taken separately at positions away from the visible shock fronts but still within the extended emission from the H ii regions permeating much of the W51 star-forming region. The raw data frames were flat-fielded with frames taken with continuum illumination of the spectrograph slit. We did not subtract dark current frames from the individual exposures but relied on the sky frames to subtract dark current.

Wavelength calibration was done using OH airglow lines recorded during the on-object integrations. The line positions were measured on the flat-fielded frames before sky subtraction. In the $H$ band, we used the OH airglow lines (wavelengths from the UKIRT Web site) at 1.63885, 1.64147, 1.64476, and 1.65023 $\mu\text{m}$ for wavelength calibration. In the $K$ band, OH lines at 2.11766, 2.12325, and 2.12497 $\mu\text{m}$ were used for wavelength calibration near the H$_2$ 1–0 $S(1)$ line. As mentioned above, Br$\gamma$ was not part of the original observing plan but was nevertheless recorded near the edge of the detector array. Wavelength calibration for Br$\gamma$ is based on extrapolation from the two OH lines at 2.17111 and 2.18022 $\mu\text{m}$. Unfortunately, we did not record any cataloged OH lines at wavelengths shorter than Br$\gamma$ in the same echelle order, limiting the accuracy of the wavelength calibration. Only the [Fe ii] line, H$_2$ 1–0 $S(1)$ and Br$\gamma$ were evaluated. Other transitions of H$_2$ were detected in the spectrum, but not with a sufficient signal-to-noise ratio to allow detailed analysis. The slit width corresponds to a velocity resolution of 22 km s$^{-1}$.

In W51, Okumura et al. (2001) have discussed near-infrared spectroscopy of the two compact H ii regions W51 IRS 2 East and West. They conclude that the faint $S(1)$ line emission in or around the H ii region is excited by fluorescence rather than shocks. This diffuse molecular hydrogen emission is distinct from the shock-excited emission discussed here for the outflow objects. However, the presence of UV-excited fluorescent $S(1)$ line emission gives a background
Fig. 2.—$H$-band, $S(1)$, and $K$-band images of the newly discovered outflows in W51.
Fig. 2.—Continued
Fig. 2.—Continued
level of line emission that is clearly detected in our spectra and not always fully removed by the sky-subtraction process owing to its spatial variation.

3. RESULTS AND DISCUSSION

3.1. Distribution of Outflow Sources

The locations of the shock-excited H$_2$ emission features are indicated on the K-band image of the wide-field survey data (Fig. 1). One group of outflows is located in dense filaments near the main H II regions associated with IRS 1 and IRS 2. The others are distributed in almost a circular pattern at larger distances of about 60 away from this central group, on the perimeter of the H II region complex. This distribution of outflow sources may be partly explained by an observational selection effect, since our detection method is clearly not as sensitive in regions superposed on or lying behind high levels of extended flux. More importantly, however, shock-excited H$_2$ emission cannot occur in fully ionized regions. In the likely case that the distribution of outflows is not entirely dominated by selection effects, it suggests that the Class 0 and Class I sources responsible for these outflows may have formed as a result of secondary star formation triggered by winds from the central H II regions and the cluster around IRS 2.

3.2. Individual Molecular Outflows and Emission Knots

The individual knots of H$_2$ emission found in this survey are named following the IAU convention. The name indicates their association with the W51 complex and their discovery by emission of the H$_2$ molecule and gives their J2000 coordinates with 1" precision. In the following, we will discuss the morphology of each candidate emission knot in detail.

3.2.1. W51H$_2$ J192318.1+142738

The H$_2$ emission W51H$_2$ J192318.1+142738 is a single, slightly elongated patch of S(1) emission, about 1.5 in north-south extent (Fig. 2a).

3.2.2. W51H$_2$ J192318.5+142656 and W51H$_2$ J192319.6+142654

The emission knots W51H$_2$ J192318.5+142656 and W51H$_2$ J192319.6+142654 are separated only by about 10". We show both of them in the high-resolution S(1) image (Fig. 3) and discuss their relationship below.

Many H$_2$ outflows in nearby star-forming regions are associated with Class 0 sources that are not directly visible at near-infrared wavelengths. Since mass accretion and the associated outflow power peak during the Class 0 phase, these extremely young sources often produce the strongest S(1) shock fronts. It would therefore be entirely plausible that the two shock fronts W51H$_2$ J192318.5+142656 and W51H$_2$ J192319.6+142654 are part of the same bipolar outflow, even though there is no positive detection of a central star that would drive the outflow.

The arguments against this scenario are based on the morphology of other extended emission features in the immediate vicinity of these two brightest emission knots. The star ≈9" north of W51H$_2$ J192318.5+142656 is the red-
The images were taken in 2000 June using QUIRC at the f/31 focus of the UH 2.2 m telescope.

The S(1) line emission in W51H2 J192322.0+143333 [H2 1–0 S(1)], showing shock-excited emission in the W51H2 J192318.5+142656 and W51H2 J192319.6+142654 shock fronts. The images were taken in 2000 June using QUIRC at the f/31 focus of the UH 2.2 m telescope.

The S(1) line emission in W51H2 J192322.0+143333 appears marginally resolved in the high-resolution image in Figure 4. The only other faint extended feature in this image is the elongated nebulosity 1" east and 3′.5 south of W51H2 J192322.0+143333 that points roughly to the latter. On morphological grounds, it could be nebulosity associated with the driving source of W51H2 J192322.0+143333, but it is too faint to be detected in the H, H2 S(1), and K survey images, so its color is unknown.

The pair of emission regions W51H2 J192323.6+142515 S and N are clearly part of the same bipolar outflow. The high-resolution S(1) image in Figure 5 reveals a feature exactly in the middle of the bright north and south regions that consists of an unresolved source and some nebulosity, separated by about 1" along the axis between W51H2 J192323.6+142515 S and N, at coordinates 19°23′23′′6 +14°25′15′′ (J2000). We label these features as W51H2 J192323.6+142515 C. Note that in this case the two shock fronts of this outflow are listed as the north and south features of an outflow listed under the coordinates of its central source. These central features are very red and are not visible at all in the H-band wide-field image. They are weakly indicated in the K-band image. This is exactly the morphology seen in many other bipolar outflow sources, where two shock fronts are seen equidistant to some scattered light near the central source. An example of this is the outflow in L1634 (Hodapp & Ladd, 1995). For comparison, the extent of the W51H2 J192323.6+142515 outflow is 30′′ between the two shock fronts, while the L1634 outflow in Orion at a distance of 500 pc is 6′2 long, nearly the same linear projected extent of ≈1 pc.

The emission knot W51H2 J192335.0+143028 is a bright, compact knot of H2 1–0 S(1) line emission. Close to it is a second emission knot W51H2 J192336.6+143014. It is noteworthy that these two emission knots are collinear with one of the reddest stars detected in our whole W51 survey area, labeled RS in Figure 6, at 19°23′32′′7 +14°30′48′′ J2000. The red star is undetected in our H-band image and appears much brighter in K (2.2 μm) than in S(1) (2.12 μm), compared to other stars in the field. Figure 6 is a larger subframe of the survey images and illustrates this collinear relationship between these features. This alignment suggests that the red star may be the driving source of a well-collimated jet of ≈2.2 pc projected length that produces the two emission knots. The degree of collimation of this jet would be quite remarkable but not unprecedented.

3.2.3. W51H2 J192322.0+143333

The S(1) line emission in W51H2 J192322.0+143333 is the elongated nebulosity 1" east and 3′.5 south of W51H2 J192322.0+143333 that points roughly to the latter. On morphological grounds, it could be nebulosity associated with the driving source of W51H2 J192322.0+143333, but it is too faint to be detected in the H, H2 S(1), and K survey images, so its color is unknown.

3.2.4. W51H2 J192323.6+142515

The S(1) line emission in W51H2 J192323.6+142515 S and N are clearly part of the same bipolar outflow. The high-resolution S(1) image in Figure 5 reveals a feature exactly in the middle of the bright north and south regions that consists of an unresolved source and some nebulosity, separated by about 1" along the axis between W51H2 J192323.6+142515 S and N, at coordinates 19°23′23′′6 +14°25′15′′ (J2000). We label these features as W51H2 J192323.6+142515 C. Note that in this case the two shock fronts of this outflow are listed as the north and south features of an outflow listed under the coordinates of its central source. These central features are very red and are not visible at all in the H-band wide-field image. They are weakly indicated in the K-band image. This is exactly the morphology seen in many other bipolar outflow sources, where two shock fronts are seen equidistant to some scattered light near the central source. An example of this is the outflow in L1634 (Hodapp & Ladd, 1995). For comparison, the extent of the W51H2 J192323.6+142515 outflow is 30′′ between the two shock fronts, while the L1634 outflow in Orion at a distance of 500 pc is 6′2 long, nearly the same linear projected extent of ≈1 pc.

3.2.5. W51H2 J192325.9+143703 and W51H2 J192327.9+143701

Two faint emission knots in close vicinity were found at the northern edge of our survey field. The two panels in Figure 2b showing W51H2 J192325.9+143703 and W51H2 J192327.9+143701 actually overlap. There is no morphological indication that the two emission knots are part of the same outflow, so, conservatively, we list them separately, as was discussed above.

3.2.6. W51H2 J192335.0+143028 and W51H2 J192336.6+143014

The emission knot W51H2 J192335.0+143028 is a bright, compact knot of H2 1–0 S(1) line emission. Close to it is a second emission knot W51H2 J192336.6+143014. It is noteworthy that these two emission knots are collinear with one of the reddest stars detected in our whole W51 survey area, labeled RS in Figure 6, at 19°23′32′′7 +14°30′48′′ J2000. The red star is undetected in our H-band image and appears much brighter in K (2.2 μm) than in S(1) (2.12 μm), compared to other stars in the field. Figure 6 is a larger subframe of the survey images and illustrates this collinear relationship between these features. This alignment suggests that the red star may be the driving source of a well-collimated jet of ≈2.2 pc projected length that produces the two emission knots. The degree of collimation of this jet would be quite remarkable but not unprecedented.
3.2.7. W51H2J192338.3+143047

The faint emission knot W51H2 J192338.3+143047 has no morphological features (Fig. 2c) that would help in identifying its driving source.

3.2.8. W51H2J192339.7+143131

The largest shock front detected in S(1) is W51H2 J192339.7+143131. It appears morphologically to be associated with a driving source in the general direction of the IRS 2 young cluster to its south. A plausible candidate for the driving source is the extremely red star at 19h23m39.8s +14°31'21" that lies close to the symmetry axis of the bow shock fronts. More detailed images in the emission lines of [Fe II] and S(1) are shown in Figure 7. The S(1) emission shows the typical shape of multiple bow shocks, while [Fe II] is generally more concentrated on the axis of the outflow, i.e., the areas of highest shock velocity and excitation. It is noteworthy, however, that the S(1) emission exhibits pronounced peaks near the apexes of two of the bow shocks, different from what is found in most other S(1) bow shocks, e.g., (Tedds, Brand, & Burton 1999). This object will be discussed in more detail below (§ 3.4) in the context of our spectroscopic data.
3.2.9. \textit{W51H}_2 J192345.5+143537

The two emission knots found in \textit{W51H}_2 J192345.5+143537 are treated as part of one system, since their close proximity makes a chance superposition of two unrelated shock fronts very unlikely. The high-resolution image in Figure 8 shows one knot clearly resolved, the other marginally resolved, but no further conclusions about the location of the driving source can be derived from these images.

3.2.10. \textit{W51H}_2 J192347.2+142944

The star labeled \textit{W51H}_2 J192347.2+142944 stands out because of its strong flux in the S(1) filter. While the star appears slightly more extended than other stars on the S(1) frame and more extended than its K-band image, the distribution of S(1) emission around the star cannot be mapped out. We conclude that the molecular emission in this region originates in the immediate vicinity of the star.

3.2.11. \textit{W51H}_2 J192403.3+143255

The emission knot \textit{W51H}_2 J192403.3+143255 is extended, but small. No obvious association with other emission knots or red stars was found that might help in identifying the driving source.

3.3. \textit{Velocity-resolved Spectroscopy of} \textit{W51H}_2 J192323.6+142515 S

A high spatial resolution image of the two H\textsubscript{2} emission features \textit{W51H}_2 J192323.6+142515 N and S is shown in
Figure 5 and was discussed in § 3.2.4. A high-resolution H$_2$ spectrum was obtained toward only the southern component at the slit position indicated in Figure 5 and is shown in Figure 9.

In knot S-A, farthest from the likely driving source, broad, double-peaked H$_2$ profiles peaking at $V_{\text{LSR}} \sim 60$ km s$^{-1}$ (just blue of the cloud systemic velocity of 70 km s$^{-1}$) and $V_{\text{LSR}} \sim 0$ km s$^{-1}$ (blueshifted by $\sim 70$ km s$^{-1}$) are observed. This velocity-split emission corresponds to two spatially separate emission knots in Figure 5. Note, however, that the separation of the two velocity components is much larger than the spectral resolution of 22 km s$^{-1}$, so the velocity split is real and not just a projection of two spatially separate knots in the slit. Behind (north of) the shock front S-A (offset $1^\prime$ in Fig. 9) the H$_2$ velocities converge to an intermediate, blueshifted velocity $V_{\text{LSR}} \sim 20$ km s$^{-1}$, spatially coinciding with a single emission knot centered on the slit.

The fainter knot S-B (not covered well by the slit) also shows a double-peaked H$_2$ profile with peaks at $V_{\text{LSR}} \sim 40$ km s$^{-1}$ and $V_{\text{LSR}} \sim -20$ km s$^{-1}$, i.e., about 20 km s$^{-1}$ more blueshifted than knot S-C. Further back toward the driving source, shock front S-C is much more diffuse than S-A and S-B, and fainter. Figure 9 shows a broad line centered at $V_{\text{LSR}} \sim 30$ km s$^{-1}$, without a clear indication of a separation into two peaks.

The observed double-peaked H$_2$ profiles, with peak-to-peak separations of $\sim 60$ km s$^{-1}$, are predicted by numerical models (Volker et al. 1999) and are implied by the analytical (Hartigan, Raymond, & Hartmann 1987) J-type bow-shock models of atomic line emission. The most extended, double-peaked profiles will be expected near the front of the bow shock; narrow, low-velocity peaks will instead be associated with the oblique wings. Indeed, the range of H$_2$ velocities observed in W51H$_2$ J192323.6+142515 S can be explained on purely geometrical grounds, if the flow is inclined toward the observer at an angle (with respect to the line of sight) of $\phi = 40^\circ$–$70^\circ$. By comparison, a bow shock moving in the plane of the sky ($\phi = 90^\circ$) would produce two (blended) peaks blue- and redshifted by the same amount, while a bow viewed head-on would produce only one, blueshifted component (see, for example, plots IV and I in the appendix in Davis, Hodapp, & Desroches 2001).

Overall, the spectral features seen in W51H$_2$ J192323.6+142515 S are quite similar to those found in HH 111 by Davis et al. (2001). They can be explained by the straightforward geometric fact that the H$_2$ emission arises in the oblique shocks in the wings of the bow shocks, where shock velocities are low despite a high velocity of the jet relative to the ambient cloud medium. The shock velocities seen in W51H$_2$ J192323.6+142515 S are just above the dissociation limit for pure J-type shocks, which suggests a certain degree of magnetic cushioning to avoid rapid dissociation of the H$_2$ molecule (Smith 1994).

3.4. Velocity-resolved Spectroscopy of W51H$_2$ J192339.7+143131

3.4.1. Morphology and Slit Orientation

The bow shocks in W51H$_2$ J192339.7+143131 indicate a much faster and powerful outflow than the outflow discussed above. High-spatial resolution images of W51H$_2$ J192339.7+143131 in [Fe ii] and H$_2$ 1–0 S(1) are shown in Figure 7. This object is situated 23° north of the IRS 2 cluster.

In H$_2$, W51H$_2$ J192339.7+143131 resembles a sequence of at least three “nested” bow shocks separated by 2″–3″, labeled A, B, and C in Figure 7. A very similar arrangement of nested bow shocks, with the larger ones being found in the wakes (i.e., toward the driving source) of smaller bow shocks, is observed in the low-mass L1634 outflow (Hodapp & Ladd 1995). The bow-shock nature of W51H$_2$ J192339.7+143131 is confirmed by high-resolution spectroscopy in the H$_2$ 1–0 S(1) and [Fe ii] lines (Fig. 10).

The [Fe ii] emission in W51H$_2$ J192339.7+143131 (Fig. 7, left) appears to be generally more closely confined to the north-south outflow axis than the H$_2$ emission. This is not unexpected since the [Fe ii] traces the higher-excitation bow-shock caps while the H$_2$ is excited in the oblique, lower excitation bow-shock wings (Davis, Smith, & Eisloffel 2000; Lorenzetti et al. 2001). However, contrary to this generalized statement, we find strong H$_2$ emission from near the apexes of the bow shocks, which we believe to result from fluorescence, as will be discussed below.

We present [Fe ii], H$_2$, and Br$_\gamma$ (Fig. 10) spectra observed through the center of W51H$_2$ J192339.7+143131. The slit was aligned to cover the brightest H$_2$ 1–0 S(1) emission knots (B and C) and is probably closely aligned with the outflow axis, if our identification of the driving source or at least the location of the driving source in the general area of IRS 2 is indeed correct. Millimeter-wave mapping of the cloud structure in W51A suggests that the LSR systemic velocity of the IRS 2 region is $\sim 61$ km s$^{-1}$ (Carpenter & Sanders 1998), although variations in the systemic velocities of cloud cores across the region are evident in the molecular cloud maps. Spatially extended S(1) emission around IRS 2, probably UV-excited in the radiation field of the O stars in IRS 2, and largely subtracted out from our sky-subtracted spectral images, is centered around 70 km s$^{-1}$. All three spectra were individually wavelength calibrated using OH airglow lines recorded on the object frames. The wavelength calibration of the Br$_\gamma$ line is relatively poor, since Br$_\gamma$ was not part of the original observing plan and was evaluated...
only when interesting structure was unexpectedly found. As a consequence, Br$\gamma$ was recorded near the edge of the detector array where optical distortions could be significant, and the wavelength calibration could be done only by extrapolation from OH lines, not by interpolation, since there were no OH lines recorded shortward of 2.166 $\mu$m in the echelle order used. The small differences in the velocity of the narrow components of S(1) and Br$\gamma$ emission are probably due to these calibration problems, and we do not believe they are significant. We adopt a systemic cloud velocity of $\sim$70 km s$^{-1}$ for IRS 2 and W51H$_2$ J192339.7+143131.

The position-velocity images in Figure 10 show very distinct features in the three emission lines studied here. The H$_2$ 1–0 S(1) emission is largely confined to a narrow velocity range around the systemic velocity. The velocity structure seen in H$_2$ 1–0 S(1) is, however, correlated to the high-velocity features seen in [Fe ii] and Br$\gamma$, in the sense that knot B shows a slight blueshift and knot C a slight redshift. Only in the faint knot A, north of the main shock fronts, does the S(1) line split, producing a weak blueshifted component, as expected for the spectrum of a nondissociative bow shock.

The [Fe ii] line is a more robust tracer of shocked gas than the rather fragile H$_2$ molecule and more closely traces the full velocity field in the shock fronts, which in this case extends over a range of 300 km s$^{-1}$. The detection of velocity features related to the shock fronts in Br$\gamma$ was a surprise. We had, of course, expected copious Br$\gamma$ emission from the nearby IRS 2 H ii regions, either projected as foreground or background emission or scattered into the line of sight. However, the Br$\gamma$ line in W51H$_2$ J192339.7+143131 shows features clearly correlated to those seen in the other two lines studied here. These features are clearly related to the outflow shock fronts and make W51H$_2$ J192339.7+143131 a rare case of outflow shock fronts with detectable Br$\gamma$ emission. We will now discuss the individual emission lines in order of wavelength.

3.4.2. The [Fe ii] Line

The [Fe ii] emission is concentrated in the region between the H$_2$ knots B and C and is less spatially extended perpendicular to the jet axis than the S(1) emission (Fig. 7). This is consistent with the fact that [Fe ii] emission should be concentrated in the high-excitation regions directly at the head of the bow shock, a region where S(1) emission is suppressed by dissociation of the H$_2$ molecule.

At the position of knot C and up to 1$''$ north of it, the [Fe ii] emission is strongly redshifted and very broad, extending from $V_{LSR} \sim 20$ km s$^{-1}$ to $V_{LSR} \sim 200$ km s$^{-1}$. Further north, up to the position of knot B, broad emission is observed with velocities ranging from blueshifted $V_{LSR} \sim -60$ km s$^{-1}$ to redshifted $V_{LSR} \sim 120$ km s$^{-1}$. Overplotted on the spectral image in Figure 10 is the normalized spectrum integrated over the relevant parts of the slit, for comparison with the model presented by Hartigan, Raymond, & Hartmann (1987). The broad, only slightly asymmetric profile measured in W51H$_2$ J192339.7+143131 closely matches the theoretical profile calculated for H$_2$ emission of their 200 km s$^{-1}$ jet model inclined by 60$^\circ$ against the line of sight toward the observer (their Fig. 3c).

In our case, the total velocity spread is larger, about 300 km s$^{-1}$, and the redshifted component is somewhat stronger and more extended than the model would predict, but the overall agreement to the idealized model is remarkably good.

The [Fe ii] spectrum shows a much wider spread of velocities than the S(1) spectra at the same slit position. Our S(1) and [Fe ii] images suggest a spatial anticorrelation between the two emission lines. S(1) is primarily emitted in front of and behind the main shock outlined in [Fe ii], since the high temperatures in this 300 km s$^{-1}$ shock dissociate the H$_2$ molecule.

In addition to the good agreement of the integrated [Fe ii] spectrum with the models by Hartigan et al. (1987), the details of the [Fe ii] spectrum, i.e., the wide velocity range observed and the prominent redshifted emission, can be explained by a fully developed hydrodynamical model.

The hydrodynamical models of Völker et al. (1999) discuss the gas motions near the apex of a jet in detail. Their Figure 13 clearly shows that, in the reference frame of the jet, gas is being pushed sideways at the apex of the jet and streams backward in the wings of the bow shock. The same models also show that the velocity field in the bow of a shock can be complex and that knots of peculiar velocities exist. In the case of W51H$_2$ J192339.7+143131, where the predominantly blueshifted and redshifted components of [Fe ii] emission are spatially separated, we have to postulate that the emission arises from distinct emission knots near the apex of the bow, the redshifted emission being on the far side of the jet and therefore receding relative to the jet, while

![Fig. 10. High-resolution spectra of W51H$_2$ J192339.7+143131 in the 1.644 $\mu$m line of [Fe ii], the 2.118 $\mu$m 1–0 S(1) line of H$_2$, and the 2.166 $\mu$m Br$\gamma$ line of H. The slit position is as indicated in Fig. 7. A normalized spectrum of the [Fe ii] emission, integrated along the slit, is overplotted. Each spectrum is given in two different linear stretches, to show faint emission features.](image)
the blueshifted emission is from the near side of the bow, moving toward the observer in excess of the jet velocity.

#### 3.4.3. The \( \text{H}_2 \) 1–0 S(1) Line

The \( \text{H}_2 \) 1–0 S(1) line in W51H2 J192339.7+143131 is strikingly narrow in an object that shows substantial line width in \( \text{[Fe ii]} \). Only the northernmost and faintest of the emission knots identified in Figure 7 (knot A) shows the split line profile expected from a bow shock seen from the side. The presence of \( \text{[Fe ii]} \) emission supports J-type shock excitation, i.e., no significant cushioning by magnetic fields. In such shocks, \( \text{H}_2 \) will be dissociated at relatively low shock velocities, of the order of 20–25 km s\(^{-1}\). The centers of the two velocity components in knot A are separated by about 50 km s\(^{-1}\), which is roughly double the dissociation shock velocity limit for \( \text{H}_2 \). The other two knots (B and C) do not show a splitting of the lines, but show slightly broadened spectral features spreading over a maximum of 50 km s\(^{-1}\), i.e., within the dissociation limit. The velocity structure is related to the velocity field seen in \( \text{[Fe ii]} \) emission in the sense that knot B exhibits a slight blueshift, while knot C is slightly redshifted. \( \text{H}_2 \) will survive and be collisionally excited into emission only in the oblique wings of the bow shocks, exhibiting narrow line profiles. An example of this are the bullets in Orion (Tedd et al. 1999) where the tips of the bows are traced in \( \text{[Fe ii]} \) and the wings in \( \text{H}_2 \) S(1). However, in our images the \( \text{H}_2 \) emission appears brightest on-axis, in the two compact knots B and C near the apex of the bow shocks, where molecules will be collisionally dissociated. We therefore postulate that the strong, spatially concentrated \( \text{H}_2 \) emission near the apex of the bow with narrow line width represents fluorescent emission from quiescent molecular material in front of the bow shock that is excited by the UV radiation field generated by the high temperature in the shock front. The presence of Br\( \gamma \) emission in the shock front is proof that temperatures high enough to dissociate \( \text{H}_2 \) and ionize \( \text{H} \) exist locally in the shock front. Fluorescent emission from \( \text{H}_2 \) in the UV has been found in IUE spectra of several HH objects by Böhm, Scott, & Solf (1991). In an object similar to W51H2 J192339.7+143131, the well-studied HH 7, the higher excitation lines of \( \text{H}_2 \) have been explained by fluorescence of \( \text{H}_2 \) in the presence of a strong UV field generated in the shock fronts (Fernandes & Brand 1995).

#### 3.4.4. The Br\( \gamma \) Line

Emission in the Br\( \gamma \) line is very rarely seen in the shock fronts of stellar outflows even though H\( \alpha \) is commonly observed in low-extinction Herbig-Haro jets and shock fronts (see Reipurth & Bally 2001 for a recent review). Br\( \alpha \) has recently been observed (Fuller, Zijlstra, & Williams 2001) in an outflow from a high-mass star. Emission of Br\( \gamma \) is, of course, expected near the H\( \pi \) region associated with IRS 2 and could arise in the foreground or background of the outflow shock fronts of W51H2 J192339.7+143131, or it could be scattered into that line of sight. Remarkably, however, the Br\( \gamma \) emission in W51H2 J192339.7+143131 shows features similar to those seen in [Fe ii] and \( \text{H}_2 \), demonstrating that a significant fraction of the Br\( \gamma \) flux originates in the outflow shock fronts themselves.

The brightest peak in the Br\( \gamma \) position-velocity image is just north of knot B. The narrow-line Br\( \gamma \) intensity south of knot B drops to 55% of its value (per pixel) just north of this knot. This indicates that ~45% of this narrow-line flux must originate close to the shock front, while ~55% may be foreground or background flux from elsewhere along the line of sight. The Br\( \gamma \) emission in knot C is more spatially extended than the \( \text{H}_2 \) emission, but they are clearly related.

At very low but clearly significant flux levels, spectra very broad Br\( \gamma \) essentially duplicate the features seen in [Fe ii]: strong blueshift in knot B and redshift in knot C, with about the same total velocity extent. This component of the Br\( \gamma \) emission is clearly related to fast moving gas in the bow shock front. The broad high-velocity Br\( \gamma \) emission is probably collisionally excited in the rapid, high-velocity shock fronts, similar to the [Fe ii] emission.

As explained above, absolute velocity calibration of the Br\( \gamma \) is rather uncertain owing to observational limitations. We therefore do not ascribe any significance to the absolute velocity difference between the \( \text{H}_2 \) 1–0 S(1) and Br\( \gamma \) lines in Figure 10.

#### 3.4.5. Synopsis of W51H2 J192339.7+143131

Of the three emission lines discussed here, [Fe ii] is a pure and robust tracer of shock-excited gas. It shows a spread of velocities over a range of 300 km s\(^{-1}\), and its integrated line profile matches simple models of bow-shock emission very well. The Br\( \gamma \) line traces both the high-velocity gas, either by direct shock excitation or UV excitation from the shock, and the low-velocity components, by UV excitation from the shock in addition to fore- and background emission. The \( \text{H}_2 \) emission traces only low-velocity gas, since \( \text{H}_2 \) dissociates in high-velocity shocks. The strong \( \text{H}_2 \) emission from the tips of the bow shocks can best be explained by fluorescent excitation of \( \text{H}_2 \) molecules in the radiation field of the shock, just prior to their being dissociated when hit by the shock directly.

An outflow system appearing superficially similar to W51H2 J192339.7+143131 are the “bullets” observed to emerge from a source in the Orion-Trapezium Cluster. A detailed study of this system, including high-resolution spectroscopy in the [Fe ii] and \( \text{H}_2 \) S(1) lines has recently been presented by Tedds et al. (1999). The shock fronts in W51H2 J192339.7+143131 appear to have a more organized large-scale shape than the system of small “bullets” in Orion, but some small-scale clumpy structure is clearly present in W51H2 J192339.7+143131. The Orion "bullets" do not show the very broad [Fe ii] profiles seen in W51H2 J192339.7+143131, and they do not exhibit the strong \( \text{H}_2 \) emission at the apex of the bow shock. Rather, they show \( \text{H}_2 \) only in the wings of the bow shocks, as expected from pure shock excitation.

Observations in [Fe ii] of the jets emanating from L1551 IRS 5 have recently been reported by Pyo et al. (2002). Their spectra along the jet axis show a similarly broad velocity profile of the [Fe ii] line to the one reported here. In contrast to our observations, theirs concentrated on the jet close to its source of origin and did not include well-developed bow shocks.

#### 3.5. The Young Stellar Cluster around IRS 2

The narrowband \( \text{H}_2 \) 1–0 S(1) line image was also used to study the young cluster surrounding IRS 2 in more detail. This image reaches about the same limiting magnitude and has better spatial resolution than the \( K \)-band image.
obtained of the wider W51 region and is therefore best suited for a rough count of the stars contained in this cluster. The $S(1)$ line image was photometrically calibrated using the standard star FS 27 (Hawarden et al. 2001) so that approximate $K$-band magnitudes could be obtained. Down to a limiting magnitude of $K = 15.3$, we count 60 stars within a projected circle of 1 pc diameter. Okumura et al. (2000) have already pointed out that one foreground star is visible in front of the W51 IRS 2 cluster, but clearly most of the stars counted around IRS 2 are physically close to this embedded source. The image (Fig. 11) also shows areas very near IRS 2 that appear as dark patches against the extended flux of the H $\alpha$ region and with virtually no stars, indicating opaque extinction. Roughly half of the 1 pc diameter circle is covered by such extinction.

The distance of 7 kpc to W51, compared to 0.5 kpc to the Trapezium Cluster, makes stars appear 5.73 mag fainter. Okumura et al. (2000) found a strong peak at $A_V = 25$ mag in their extinction histogram of “region 3” that contains the young embedded cluster associated with IRS 2. We take $A_V = 25$ here as an estimate of the extinction to those stars in the cluster that are not completely obscured, obviously an extreme simplification of the actual situation. Similar $A_V$ values were found for many of the stars in the immediate vicinity of IRS 2 by Goldader & Wynn-Williams (1994). While infrared excess may be partly responsible for the red colors leading to these extinction estimates, we assume here that stars in the W51 IRS 2 cluster suffer about $A_K = 2$ mag more extinction than the low-extinction stars seen in the Orion Trapezium (Herbig & Terndrup 1986). This statement obviously excludes the high-extinction objects in the BN/KL region. Combining the effects of distance modulus and extinction, stars in the W51 IRS 2 cluster appear about 7.7 mag fainter than they would in the Orion Trapezium Cluster. Our limiting $K$-band magnitude of 15.3 in the high-resolution image in Figure 11 corresponds to a magnitude of 7.6 in Orion. On the 2MASS $K$-band frame we count 15 stars brighter than $K = 7.6$ mag in a circle of projected diameter of 1 pc, using photometry in the Trapezium Cluster from McCaughrean & Stauffer (1994).

In comparing the young stellar clusters associated with the Orion Trapezium and W51 IRS 2, we can reach a few tentative conclusions, despite the uncertainties in the estimates for extinction and the incompleteness of the star count due to opaque areas obscuring about half the cluster, if we assume a roughly spherical intrinsic distribution of the stars. The star count in the W51 IRS 2 cluster appears to be between 4 and 8 times higher than in the Trapezium Cluster. This is roughly consistent with the count of O stars by Goldader & Wynn-Williams (1994) (four in Trapezium vs. probably nine in W51 IRS 2).

4. CONCLUSIONS

Our $H$, $H_2$ 1–0 $S(1)$, and $K$-band survey of the W51 GMC resulted in the discovery of 14 $H_2$ shock fronts associated with stellar outflows. The outflows are found in dense molecular filaments near the central H $\alpha$ regions and the young embedded cluster associated with IRS 2 and near the perimeter of the molecular cloud complex, away from the H $\alpha$ regions. We speculate that the outflows near the perimeter represent a secondary, triggered phase of star formation in W51.

Detailed, high-resolution images were used to identify plausible candidates for the driving sources of some of the outflows. For two of the outflow shock fronts, high-resolution spectroscopy was obtained. Of particular interest are the shock fronts W51H$_2$ J192339.7+14313. The very broad [Fe I] line seen in this shock front is in good agreement with models developed by Hartigan et al. (1987) for other atomic lines in shock fronts. Refinements of these models based on the hydrodynamic models of Völk et al. (1999) lead to a satisfactory agreement with the observations, even though the large observed line width and the large redshifted component remain quite remarkable. We also report the very rare detection of high-velocity Br$\gamma$ emission from this outflow, with a high-velocity component essentially matching the [Fe I] profiles. The strong, narrow $H_2$ 1–0 $S(1)$ emission found near the apex of the shock fronts strongly suggests fluorescence as the excitation mechanism for $H_2$ at this location. The outflow W51H$_2$ J192339.7+14313 is driven by a source associated with the IRS 2 young embedded cluster. Based on star counts and rough extinction estimates, we conclude that this cluster is more massive, richer in stars and richer in high-mass stars than the Orion-Trapezium Cluster, in agreement with previous results by others.

The imaging data presented here were obtained at the University of Hawaii 2.2 m telescope. The high-resolution spectroscopy presented here is based on data obtained at the W. M. Keck Observatory, which is operated as a scientific partnership among the California Institute of Technology, the University of California, and the National Aeronautics and Space Administration. The Observatory was made possible by the generous financial support of the W. M. Keck Foundation.

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