NICMOS OBSERVATIONS OF SHOCKED H$_2$ IN ORION

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ABSTRACT

HST NICMOS narrowband images of the shocked molecular hydrogen emission in OMC-1 are analyzed to reveal new information on the BN/KL outflow. The outstanding morphological feature of this region is the array of molecular hydrogen “fingers” emanating from the general vicinity of IRc2 and the presence of several Herbig-Haro objects. The NICMOS images appear to resolve individual shock fronts. This work is a more quantitative and detailed analysis of our data from a previous paper. Line strengths for the H$_2$ 1–0 S(4) plus 2–1 S(6) lines at 1.89 $\mu$m are estimated from measurements with the Paschen–$\alpha$ continuum filter F190N at 1.90 $\mu$m and continuum measurements at 1.66 and 2.15 $\mu$m. We compare the observed H$_2$ line strengths and ratios of the 1.89 and 2.12 $\mu$m 1–0 S(1) lines with models for molecular cloud shock waves. Most of the data cannot be fit by J-shocks but are well matched by C-shocks with shock velocities in the range of 20–45 km s$^{-1}$ and preshock densities of $10^4$–$10^6$ cm$^{-3}$, similar to values obtained in larger beam studies which averaged over many shocks. There is also some evidence that shocks with higher densities have lower velocities.

Subject headings: H II regions — infrared: ISM: lines and bands — ISM: individual (OMC-1) — ISM: jets and outflows — stars: pre–main-sequence

1. INTRODUCTION

At 450 pc, the Orion molecular cloud is the nearest and best-studied region of massive star formation. The Trapezium stars, formed within Orion molecular cloud 1 (OMC-1), have cleared a cavity at the near edge of the cloud. The visible Orion Nebula is the thin layer of photoionized gas on the cavity’s surface facing the observer. Behind M42, and further from the observer, is a photodissociation region (PDR) also excited by the Trapezium. The BN/KL region lies still deeper in the cloud, beyond both the ionized gas and the PDR. This region contains embedded sources with one or more associated outflows; the total luminosity of this region approaches $10^5 L_{\odot}$ (Genzel & Stutzki 1989). The mid-infrared source IRc2 had long been thought to be the origin of these outflows; but Dougados et al. (1993) resolved IRc2 into four sources, raising the possibility that none of them is sufficiently powerful to drive the observed outflows. Menten & Reid (1995) suggested that the origin may be closer to the infrared source “n” (Lonsdale et al. 1982), located $\approx 5'$ southwest of IRc2. Greenhill et al. (2004) detected extended emission from source n at wavelengths out to 22 $\mu$m but estimated a luminosity of only 2000 $L_{\odot}$. They also resolved IRc2 into about five knots and suggested that these sources together with radio source I (Churchwell et al. 1987) comprise at least part of the core of a high-density star-forming cluster.

The most striking of the molecular hydrogen outflows is a $\sim 3'$ (0.4 pc) sized, butterfly-shaped region of H$_2$ emission, centered to the north of BN, which exhibits line ratios typical of shock excitation (Beckwith et al. 1978). From O i emission, Axon & Taylor (1984) identified a number of optical HH objects in this vicinity. Taylor et al. (1984) discovered peculiar linear H$_2$ structures in the outflow. Allen & Burton (1993, hereafter AB93) showed that these H$_2$ “fingers” and all the associated optical HH objects at the far northern end of the outflow (approximately 120$''$ from BN) terminated in knots of Fe ii emission. Stolovy et al. (1998) found additional H$_2$ fingers within 30$''$ of BN. Schultz et al. (1999, hereafter Paper I) found that only 2 of the 15 inner fingers seen by Stolovy et al. (1998) had bow shocks capped by Fe ii emission, suggesting a lower excitation than in the outer fingers seen by AB93.

From offsets between the peak H$_2$ emission and the peak H$_2$ velocity, Gustafsson et al. (2003) suggested that the H$_2$ emission arises in part from outflows from protostars within dense clumps of gas. In contrast, based on proper-motion studies of optical features, Doi et al. (2002) found that both finger systems could have been created by an explosive event close to the IRc2-BN complex which took place approximately 1000 yr ago. Interestingly, Rodríguez et al. (2005) and Gómez et al. (2005) suggested that BN and sources I and n were originally part of a multiple massive stellar system that disintegrated about 500 yr ago. Explanations for the unique system of fingers have focused on two theories. AB93 originally suggested that they are “bullets”: ejected clumps leaving a wake of shocked material behind them. However, the observed morphology of the H$_2$ emission is inconsistent with models for bullets (Stone & Norman 1992; Klein et al. 1994; Xu & Stone 1995; Jones et al. 1996). These models predict that rapidly moving clumps are fragmented and that the tails should be pointing away from the ejection source, which is not seen. Stone et al. (1995) suggested the features are produced when a faster wind collides with a slower, older outflow. Rayleigh-Taylor instabilities from the collision form the clumps in situ, moving at the speed of the older outflow. The observed fingers then condense behind the slowly moving clumps. This is similar to the mechanism thought to have produced the cometary knots in the Helix Nebula (O’Dell & Handron 1996). One prediction of this model is that a region of clumpy H$_2$ emission will form behind (i.e., upstream of) the bullets. McCaughrean & Mac Low (1997) claimed to have found this clumpy emission in the central region of the H$_2$ outflow. However, our previous work (Paper I) and that of Stolovy et al. (1998) shows that much of this “clumpy” H$_2$ emission is resolved into more discrete objects, some resembling additional fingers.

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The remaining, unresolved clumpy emission is often mixed with the inner fingers.

Here we discuss the interpretation of our previously published NICMOS infrared images of a 90″ wide region centered on BN/KL, focusing on the structure of the H$_2$ emission. Examination of the F190N images, originally obtained for subtracting continuum from the PAO 1.87 μm images (Paper I), suggested that in many regions there was a strong correlation with the H$_2$ 1–0 S(1) 2.12 μm continuum-subtracted images. In fact, the F190N filter bandpass includes both the H$_2$ 1–0 S(4) and the 2–1 S(6) lines at 1.89 μm. This H$_2$ emission is likely produced in shocks (Gautier et al. 1976). The H$_2$ emission could also be produced through UV fluorescence, but larger beam studies of multiple H$_2$ transitions by Usuda et al. (1996), Rosenthal et al. (2000), and many others have shown that the measured line ratios in this region are consistent only with thermal excitation and not UV fluorescence. In this paper we focus on the finger-like structures and the HH objects. Some of these objects have optical counterparts, which places constraints on their position within the cloud/nebula interface. In § 2 we discuss the observations and data reduction. In § 3 we compare the observed H$_2$ line brightnesses with several classes of shock models in order to determine shock types, shock velocities, and gas densities. In § 4 we discuss the morphology of, and emission from, many of the more distinct, brighter features seen in our images.

2. OBSERVATIONS

Observations were made of H$_2$ 1–0 S(1) 2.12 μm and 1–0 S(4) plus 2–1 S(6) 1.89 μm in the 1% bandpass NICMOS filters. The initial reduction of the NICMOS data was described in detail in Paper I and generally followed standard procedures. Photometry was then performed on the reduced data from Paper I using the IRAF (Tody 1993) task polphot, in which the average brightness is estimated inside a user-defined polygonal aperture. The apertures were designed to closely follow the outline of each object we identified. Sky subtraction was not performed with the polphot task, but separately using a region or regions far from areas of obvious emission. Regions selected for photometry are shown in Figure 1. Knot designations, except for HH 208, utilize the source identification scheme of O’Dell & Wen (1994). Knot identifications for HH 208 are shown in Figure 11 (discussed in § 4.2.1). The features were selected for being distinct and fairly bright, having detectable 1.66 and 2.15 μm continuum emission and 2.12 μm line emission. Knot U was also included even though it had no detectable 1.66 μm continuum. The resulting photometry is listed in columns (2)–(5) of Table 1. The formal statistical errors are such that the signal-to-noise ratios (S/Ns) of all the measurements in Table 1 exceed 25 except for three: (1) the 1.66 μm measurement of 128–248 (S/N = 4), (2) the 1.66 μm measurement of HH 208U (not detected), and (3) the 2.15 μm measurement of HH 208U (S/N = 15).

There are no continuum observations for the H$_2$ 1.892 μm 1–0 S(4) plus 2–1 S(6) images. However, we did observe continua at 1.66 and 2.15 μm, intended as continua for the Fe II and 1–0 S(1) lines, respectively. The 1.89 μm continuum has been estimated from these continuum measurements by linearly interpolating between the 1.66 and 2.15 μm photometric measurements. The continuum interpolation approach was checked by applying the same technique to nine regions with no 2.12 μm H$_2$ emission. In these test regions, the interpolated continuum value was, on average, 99% ± 3% of the value actually measured in the F190N filter, confirming that this is a reasonable approach. As an example of the interpolation, the brightnesses for 128–248 with the estimated continua are shown in Figure 2.

The extinction corrections in this region are complex and vary depending on the distribution of intervening dust, which lies not only within the molecular cloud but also in the PDR and in foreground material. Extinction estimates are also complicated by reflection off the back side of the nebula. Most of our objects, including two fingers and several more compact structures, have some associated Fe II (1.64 μm) emission (A. S. B. Schultz et al. 2008, in preparation). For these objects, the 2.12 μm extinction can be estimated from the results of Chrysostomou et al. (1997), who used measurements of the Fe II 1.257 and 1.644 μm transitions, and the extinction curve of Cardelli et al. (1989) to obtain the extinction values of 0.6 shown in column (6) of Table 1. For five regions, no Fe II emission is seen, possibly because of larger extinction. The extinction for these particular objects has not been estimated by Chrysostomou et al. (1997) or others. The best references are large beam extinction studies of the H$_2$ peak 1 source. The largest and most recent such study is that of Rosenthal et al. (2000), based on the ISO measurement of 56 H$_2$ transitions covering wavelengths of 2–17 μm. They find $A_K = 1.0 ± 0.1$, a value we adopt here for 128–248, 137–239, 137–240, 143–225, and 145–204. For wavelengths other than 2.12 μm, the brightnesses have been extinction-corrected using $A_{1.89} = A_{2.12}(1.89/2.12)^{1.61}$ by Cardelli et al. (1989), who also found that the shape of the extinction curve in the infrared is independent of the value assumed for $R_V$. Usage of different plausible extinction corrections, within the uncertainties, does not appreciably alter our conclusions. For reference, we show in column (7) of Table 1 the approximate visual extinctions, $A_V = 4.5$ and ~8, based on $R_V = A_V/F_0(6700)$ = 3.1 and Cardelli et al. (1989). The final 1.89 μm H$_2$ line-to-continuum ratios range from 0.25 to 1.1, with a median of 0.7.

3. SHOCKED EMISSION FEATURES:
LINE RATIO ANALYSIS

Early shock models of the Orion outflow invoked planar C-type shock models to explain the emission from species such as H$_2$ and CO (e.g., Draine & Roberge 1982; Chernoff et al. 1982). The
C-type, or “continuous,” shocks occur at relatively low shock speeds ($V_{\text{shock}} \lesssim 50 \text{ km s}^{-1}$) in the presence of magnetic fields. A low ionization fraction allows ionized gas to cushion the shock in the neutral gas, limiting the neutral gas temperature to less than several thousand kelvins and preventing significant dissociation. The J-type, or “jump,” shocks generally occur at relatively high shock speeds ($V_{\text{shock}} \gtrsim 50 \text{ km s}^{-1}$) and usually dissociate molecular gas in the high-temperature ($T \sim 10^4$–$10^5 \text{ K}$) postshock region. Molecules re-form in the cooling postshock gas at $T \sim 500 \text{ K}$. For preshock densities $\gtrsim 10^5 \text{ cm}^{-3}$, H$_2$ line ratios produced in the re-forming molecular gas may reach values higher than thermal values, since H$_2$ re-forms in excited states, leading to a nonthermal cascade through rovibrational states (Hollenbach & McKee 1989).

Observations of shocked H$_2$O emission in Orion (e.g., Harwit et al. 1998) seem to confirm the general picture that C-type shocks are responsible for the molecular emission in the outflow. These studies converge on preshock conditions $n$(H$_2$) $\sim 10^5 \text{ cm}^{-3}$ and $V_{\text{shock}} \sim 35 \text{ km s}^{-1}$ (e.g., Chernoff et al. 1982). It should be noted, however, that these studies fit data collected from a beam area covering an entire outflow lobe ($\sim 1.1 \times 0.13 \text{ pc}$ at Orion). Images of the shocked emission on subarcsecond scales (AB93; Stolovy et al. 1998) show many emission features, each of which presumably has its own shock conditions. What is unique about the NICMOS observations of the inner region is that the 0.2$''$ ($\sim 1.4 \times 10^{15} \text{ cm}$) resolution allows the isolation of individual shock fronts on the length scales expected for such shocks. These scales are expected to be $\sim 10^{15} \text{ cm}$, depending on the preshock density but with only a weak dependence on the shock velocity (Kaufman & Neufeld 1996). This means that our deduced shock parameters are more likely to represent the local physical conditions, rather than an average over a number of shocks.
Observations with adaptive optics of H$_2$ in the ambient molecular cloud to the southeast of BN/KL have been carried out with 0.15″ angular resolution (Vannier et al. 2001; Kristensen et al. 2003). The observed H$_2$ 1–0 $S(1)$ brightness is well matched by C-shock models with shock velocities of 30 km s$^{-1}$ and preshock densities of 10$^6$ cm$^{-3}$, but the same models fall short of matching the 2–1 $S(1)$ brightness by a factor of ~2 (Vannier et al. 2001). Higher shock velocity models improve the 2–1 $S(1)$ brightness prediction but provide a worse fit to the 1–0 $S(1)$ brightness. The J-shock models produce the observed 2–1 $S(1)/1–0$ $S(1)$ brightness ratio but have trouble reproducing the individual line brightnesses. Pineau des Forêts & Flower (2001) suggested that nonstationary C-shocks can reproduce the high brightness and the large observed 2–1 $S(1)/1–0$ $S(1)$ brightness ratios. However, nonstationary C-shocks have difficulty accounting for the nonstationarity of the C-shocks.

The precise structure of the C-shocks depends on the field strength, as well as the ionization fraction, grain size distribution, and details of the gas cooling. We have previously explored the effects of varying these parameters on shock structure (Kaufman & Neufeld 1996). We find that while the precise value of shock velocity and density determined from a line ratio may vary from those presented here, the range of intensities and line ratios possible in C-shock models is essentially limited by the temperature at which H$_2$ dissociates. Thus, our conclusion that C-shocks can explain the emission in most of the observed features is robust even if the precise shock parameters are different from those we have assumed.

At this assumed magnetic field strength, low-velocity shocks are C-shocks and not the lower magnetic field strength, non-dissociative, molecular J-shocks discussed by Wilgenbus et al. (2000). Typically, molecular J-shocks produce a factor of 10–1000 times fainter H$_2$ emission in the lines discussed here than C-shocks (Wilgenbus et al. 2000). Since these line fluxes would be undetectable, we have not included nondissociative, molecular J-shocks in our grid of models. Higher velocity shocks would be dissociative J-shocks, which we do consider. In addition, C-shocks are known to be unstable to the Wardle instability (Wardle 1990) arising from perturbations in the magnetic field direction, an effect which is not taken into account in the steady-state C-shock models presented here. The effects of this instability on the strengths of H$_2$ emission lines have been explored by Mac Low & Smith (1997) and Neufeld & Stone (1997). Both studies reached the conclusion that, for shocks over the range of densities and shock velocities we consider (i.e., shocks for which H$_2$ is the dominant coolant), the instability has little effect on the predicted intensities of H$_2$ lines. Thus, our steady-state models should be sufficient for modeling the emission presented here. Clearly, changing the assumptions in the shock models—bow shocks instead of plane-parallel shocks,

![Fig. 3.—Predicted $[0.64B]1–0$ $S(4) + 0.98B[2–1 S(6)]/1–0$ $S(1)$ line ratio from C-shock and J-shock models with magnetic fields oriented perpendicular to the shock propagation direction and strengths in microgauss equal to the square root of the density in cm$^{-3}$ (Troland & Heiles 1986). Results are shown for C-shock models with $n(H_2) = 10^5$, $10^6$, and $10^7$ cm$^{-3}$ and $V_{shock} = 15–50$ km s$^{-1}$ and for J-shock models with $n(H_2) = 10^5$, $10^6$, and $10^7$ cm$^{-3}$ and $V_{shock} = 30–100$ km s$^{-1}$. Also shown is the mean value of the line ratio for the Orion feature 128–248 (horizontal solid line), with the statistical uncertainty in the ratio indicated by the dashed lines.](image-url)
This feature are best fit by a C-shock model with a velocity of either C- or J-shocks. However, the line ratio and brightness from Figure 3 as a function of shock velocity. Also shown is the measured line ratios are consistent with C-shocks having laid. Within the systematic measurement uncertainties, all but one level. The log of the preshock density falls by 45 km s⁻¹, which corresponds to an assumed magnetic field of 0.25 mG.

The predicted brightness ratio \( \frac{B[1-0 \ S(1)]}{B[1-0 \ S(4)]} \) from each model calculation is shown in Figure 4 as a function of shock velocity. Also shown is the measured ratio, 0.19, for 128–248. The line ratio is consistent with either C- or J-shocks. However, the line ratio and brightness from this feature are best fit by a C-shock model with a velocity of 36 km s⁻¹ and preshock density of 6 × 10⁴ cm⁻³. The brightnesses, line ratios, and model predictions for 128–248 are listed in Table 2. The model values are well within the systematic measurement uncertainties. The J-shock models produce absolute intensities which are too low to match the observed values.

The extinction-corrected line ratio for each of 10 locations in HH 208 and 13 other features is plotted versus their 2.12 μm H₂ line brightness in Figure 4. The shock model curves are overlaid. Within the systematic measurement uncertainties, all but one of the observed line ratios are consistent with C-shocks having preshock densities of 10⁴–10⁵ cm⁻³ and shock velocities of 25–45 km s⁻¹. The narrow range of shock velocities is not surprising. Slower C-shocks produce much weaker H₂ emission and would not have been detected. Faster C-shocks break down into J-shocks, again with much fainter H₂ emission because the H₂ is dissociated. The consistency with larger beam studies does suggest that these studies yield reasonable average shock parameters. Table 3 lists shock velocities and preshock densities for all the objects. These values were estimated by interpolating within the grid of calculated C-shock models at densities of 10⁴, 10⁵, and 10⁶ and shock velocities of 20, 25, 30, 35, and 40 km s⁻¹, whose curves are plotted in Figure 4. Extrapolations for those objects just outside the grid were made using a few additional models with shock velocities of 45 km s⁻¹. Two objects, 143–239 and HH 208A, are clearly outside the C-shock grid.

Examination of Figure 4 suggests that higher shock velocities may be correlated with lower preshock densities. A variety of statistical tests show that this correlation is significant at the 3–4 σ level. The log of the preshock density falls by ~0.6 for each shock velocity increase of 10 km s⁻¹. In order to search for structure such as the “hot edges” found by Kristensen et al. (2003), we have constructed and examined images of the line flux ratio for all 23 of the features included in Figure 4. We find no significant structure in the ratio images except for 145–204 and 159–242, where there is a peak in the line ratio offset by \( 10^{1.2 - 2} \) from the peak H₂ 1–0 S(1) emission.

### 4.1. Fingers

The array of inner fingers which comprises the butterfly-shaped H₂ emission first found by Beckwith et al. (1978) extends over a 90° broad region. Most of the northern H₂ fingers (AB93) are outside of our field to the north, but there are additional fingers to the south, east of the Trapezium (McCaughran & Mac Low 1997). The velocity measurements of Chrysostomou et al. (1997) found that in addition to strong, broad H₂ emission over the entire source, there are high-velocity components confined to discrete condensations. The high-velocity components are ascribed to additional “bullets” similar to those imaged in the northern fingers by AB93. At our higher angular resolution, the morphology of the inner fingers (Fig. 1) is quite varied. Some of the objects are

![Diagram](image-url)

**Table 2**

| Type | \( 0.64B[1-0 \ S(4)] + 0.98B[2-1 \ S(6)] \) (erg s⁻¹ cm⁻² sr⁻¹) | \( B[1-0 \ S(1)] \) (erg s⁻¹ cm⁻² sr⁻¹) | \( 0.64B[1-0 \ S(4)] + 0.98B[2-1 \ S(6)]/B[1-0 \ S(1)] \) |
|------|-------------------------------------------------|-------------------------------------------------|-------------------------------------------------|
| Observed | 2.57 × 10⁻³ | 1.36 × 10⁻² | 0.190 |
| Model* | 2.60 × 10⁻³ | 1.31 × 10⁻² | 0.198 |

* Model parameters: \( \varepsilon_0 = 36 \) km s⁻¹ and \( n = 6.3 \times 10^4 \) cm⁻³, which corresponds to an assumed magnetic field of 0.25 mG.
revealed to be bright, well-defined bow shocks; others do not display distinct bows of any kind. Most of the objects are found to have complex structure, with what appear to be internal shocks.

4.1.1. 128–248 and 135–246

Object 128–248 is a bright, well-defined bow shock in the southwestern portion of the finger array. Because it is so bright and well-separated from the main array by dark dust lanes, 128–248 is an excellent candidate for many studies. A. S. B. Schultz & M. G. Burton (2008, in preparation) found a FWHM of $30 \text{ km s}^{-1}$/C0, while Chrysostomou et al. (1997; their object 10) found that it has a FWHZ of $50 \text{ km s}^{-1}$. A. S. B. Schultz & M. G. Burton (2008, in preparation) and Gustafsson et al. (2003; their region 11) found that its line profile has no secondary line peaks, which is surprising for a bow shock and almost unique among the inner fingers. From its peak velocity of $0 \text{ km s}^{-1}$, Gustafsson et al. (2003) concluded that 128–248 is moving in the plane of the sky, but they were unable to determine in what direction. The H2 emission morphology, shown in Figure 5, is a classic bow-shock shape which appears to be moving to the southwest. From the line fluxes, we deduce a shock velocity and preshock density of $36 \text{ km s}^{-1}$ and $10^{4.8} \text{ cm}^{-3}$ for 128–248.

Object 135–246 is a bright bow shock at the end of a faint finger emerging from a extended continuum "tail" of IRc4 (see Fig. 1). It is prominent in H2 1–0 S(1), Fe II (A. S. B. Schultz et al. 2008, in preparation), and the F190N and F215N continuum bands. The object also appears in O I and possibly in S II emission (A. S. B. Schultz et al. 2008, in preparation). Our H2 image is shown in Figure 5; from the line ratios we deduce a shock velocity and preshock density of $45 \text{ km s}^{-1}$ and $10^{4.8} \text{ cm}^{-3}$. The northeastern boundary of the bright tip of the 135–246 bow shock is very sharp. We suggest this is probably due to the emergence of the finger from behind a region of high extinction: Figure 6 shows that the southwestern extent of the H2 finger is partially obscured by the same dark, curving dust lanes which are near 128–248 and the region south of BN.

4.1.2. 137–239, 137–240, and 140–239

The H2 emission from 137–239, 137–240, and 140–239 is shown in Figure 7. From our analysis, 137–239, 137–240, and 140–239 are all fit by shock velocities of $32–33 \text{ km s}^{-1}$ and preshock densities of $10^{4.7–4.8} \text{ cm}^{-3}$. Object 140–239 is a small knot $300''$ south of IRc4. NICMOS H2 images (Stolovy et al. 1998) suggest that this object may be a bow shock, perhaps coming toward us at a low angle because of its relatively large blueshift (A. S. B. Schultz et al. 2008, in preparation). The lower spatial resolution of Chrysostomou et al. (1997) combined 137–239 and 137–240 into a single feature, which they identified as a high-velocity "bullet" (No. 5 in their list) with a FWZI of 100 km s$^{-1}$. The two features were also observed together in H2 1–0 S(0) as object b of

### Table 3: Estimated C-Shock Velocities and Preshock Densities

| Position       | $v_s$ (km s$^{-1}$) | $n_{H2} \log{10}$ (cm$^{-3}$) |
|----------------|---------------------|-------------------------------|
| HH 208B        | 42                  | 4.5                           |
| HH 208D        | 32                  | 4.8                           |
| HH 208E        | 36                  | 4.5                           |
| HH 208F        | 33                  | 4.6                           |
| HH 208J        | 32                  | 4.8                           |
| HH 208N        | 27                  | 5.2                           |
| HH 208P        | 40                  | 4.5                           |
| HH 208R        | 26                  | 5.5                           |
| HH 208U        | 42                  | 4.0                           |
| 128–248        | 36                  | 4.8                           |
| 135–246        | 45                  | 4.0                           |
| 137–239        | 32                  | 4.8                           |
| 137–240        | 33                  | 4.8                           |
| 140–239        | 32                  | 4.7                           |
| 142–240        | 42                  | 4.3                           |
| 143–225        | 27                  | 5.8                           |
| 144–237        | 38                  | 4.3                           |
| 145–204        | 33                  | 4.6                           |
| 152–229        | 27                  | 5.0                           |
| 159–242        | 41                  | 4.5                           |
| 161–246        | 42                  | 4.4                           |

* Assumes planar shock propagating into a perpendicular magnetic field with strength in microgauss equal to the square root of the density in cm$^{-3}$ (Troland & Heiles 1986).

![Fig. 5.—H2 1–0 S(1) image of 128–248 and 135–246. North is up, and east is to the left. The maximum brightness is $8.9 \times 10^{-3} \text{ ergs s}^{-1} \text{ cm}^{-2} \text{ sr}^{-1}$.](image)

![Fig. 6.—The 2.12 μm continuum plus H2 1–0 S(1) line map showing the locations of 128–248, 135–246, 137–239, and 137–240 relative to the dust lanes and BN. The Trapezium is off the bottom of the image. North is up, and east is to the left.](image)
Lacombe et al. (2004). The morphology in that line was essentially identical to the morphology in $1-0\,S(1)$. Gustafsson et al. (2003) found these objects to have a peak velocity of $-25\,\text{km\,s}^{-1}$, although they do not indicate whether they were able to distinguish between the two bow shocks. A. S. B. Schultz & M. G. Burton (2008, in preparation) find a velocity closer to $50\,\text{km\,s}^{-1}$ for 137–239. In Figure 6 we suggest how 137–239 and 137–240 may also be emerging from a dust lane, like 135–246.

4.1.3. 142–240, 143–239, and 144–237

These three objects are shown in $H_2\,1-0\,S(1)$ emission in Figure 8. Object 142–240 is a blunt, bow-shaped object southeast of the star at the head of IRc4. It is bright in $H_2$ and $Fe\,\Pi$ and much fainter in $S\,\Pi$ and $O\,I$ (A. S. B. Schultz et al. 2008, in preparation). The $Fe\,\Pi$ emission (A. S. B. Schultz et al. 2008, in preparation) is more extended than the $H_2$, suggesting these transitions sample different regions. For 142–240 we deduce a C-shock velocity of $42\,\text{km\,s}^{-1}$ and a preshock density of $10^{4.3}\,\text{cm}^{-3}$. Object 142–240 is accompanied on its eastern side by a fainter, larger bow-shaped region of $Fe\,\Pi$ emission, 143–239, which is not seen in $S\,\Pi$ and $O\,I$ (A. S. B. Schultz et al. 2008, in preparation). From its $H_2$ emission, which is blueshifted (A. S. B. Schultz & M. G. Burton 2008, in preparation), 143–239 appears to arise from a J-shock; from Figure 4 the velocity and density would be in excess of $100\,\text{km\,s}^{-1}$ and $10^{7}\,\text{cm}^{-3}$, respectively. A density this high might be expected to produce water masers, and indeed, Gaume et al. (1998) find a water maser within the error box of 143–239. Object 143–239 connects to 144–237, a bright knot of $Fe\,\Pi$ (A. S. B. Schultz et al. 2008, in preparation) and $H_2$ emission $4.4''$ to the northeast of 142–240. Similar to 143–239, 144–237 exhibits blueshifted emission (A. S. B. Schultz & M. G. Burton 2008, in preparation), with a deduced shock velocity of $38\,\text{km\,s}^{-1}$ and a preshock density of $10^{4.3}\,\text{cm}^{-3}$. There is also faint $Fe\,\Pi$ emission slightly ($\sim0.6''$) north of the $H_2$ emission (A. S. B. Schultz et al. 2008, in preparation). If this $Fe\,\Pi$ is associated with 144–237, it may be that 144–237 is moving in the direction of BN or that the bow shock is asymmetric.

4.1.4. 152–229 and 143–225

Chrysostomou et al. (1997) identified 152–229 as a bow shock (their bullet 6). Our $H_2$, $Fe\,\Pi$, and 2.15 $\mu$m continuum emission is shown in Figure 9. O’Dell et al. (1997a) found that $S\,\Pi$ emission in
this region is blueshifted. Gustafsson et al. (2003) found a peak velocity of $-21$ km s$^{-1}$ and a displacement of 0.2" between the emission peak and the location of maximum velocity. From the direction of this displacement, they deduced that the shock is propagating toward BN (roughly between 2 and 3 o’clock in Fig. 9). In disagreement with Gustafsson et al. (2003), Doi et al. (2002) found from the proper motion of the $\text{S}_2$ emission that 152–229 is moving slightly north of east, away from BN/IRc2, with a transverse velocity of 50 km s$^{-1}$. Chrysostomou et al. (1997) found that 152–229 has a FWZI of 110 km s$^{-1}$. The estimated shock velocity and preshock density are 27 km s$^{-1}$ and 10$^{4.5}$ cm$^{-3}$. Paper I noted that the H$_2$ knot has a pointed cap of Fe $\pi$ emission on the southeast side of the object (the blue arc in Fig. 9), away from the putative exciting source (BN/IRc2) of the outflow. The positioning and morphology strongly suggests a bow shock in which strong shocks producing the Fe $\pi$ emission form on the leading surface of the bow while weaker shocks producing H$_2$ emission form behind it. The cap is also seen in the S $\pi$ and O $\iota$ images of O’Dell et al. (1997a) and is possibly also visible in high-velocity S $\pi$ emission (O’Dell et al. 1997b); this may be the unlabeled S $\pi$ knot northeast of 147–234.

Chrysostomou et al. (1997) also identified 143–225 as a bow shock (their bullet 8) with a FWZI of 140 km s$^{-1}$. Object 143–225 is among the most blueshifted features in the outflow (A. S. B. Schultz & M. G. Burton 2008, in preparation) and may be a bow shock approaching us at a low angle. The H$_2$ emission is shown in Figure 10. The deduced shock velocity and preshock density are 27 km s$^{-1}$ and 10$^{4.8}$ cm$^{-3}$. The shape suggests that it is a bow shock pointed slightly north-northwest, which would mean the origin of the feature would be somewhere to the south-southeast, roughly opposite of the direction of BN.

4.2. Knots

4.2.1. H$\text{H}$ 208

H$\text{H}$ 208, approximately 7" west of BN, was first discovered by Axon & Taylor (1984). The S $\pi$ and O $\iota$ HST images of O’Dell et al. (1997b) clearly show a number of small features. Based on S $\pi$ and O $\iota$ images, O’Dell et al. (1997a) identified three knots in H$\text{H}$ 208. The detection of optical features suggests that the extinction to H$\text{H}$ 208 is lower than to other H$_2$ features, implying that it lies more in the foreground. Figure 11 shows our H$_2$, Fe $\pi$, and continuum images, along with our knot identifications. The H$\text{H}$ 208 H$_2$ emission takes the form of discrete clumps, whereas the adjacent H$_2$ emission has a more finger-like appearance. It is difficult to discern what process has created this collection of features.

Knot A is the faintest of the 2.12 $\mu$m H$_2$ knots, but it is the original H$\text{H}$ 208, seen in both S $\pi$ and O $\iota$. O’Dell et al. (1997b) showed images of knot A in several filters and noted that a line drawn through H$\text{H}$ 208 and H$\text{H}$ 208NW terminates near the proplyd 154–240. They suggested that 154–240 may be the source of H$\text{H}$ 208, but the line drawn (which is symmetric through H$\text{H}$ 208NW but not through the rest of the object) also falls near IRc2 and radio sources I and n. Doi et al. (2002) found no net proper motion of knot A. The structure of the bright core of knot A did change in a disorganized fashion between 1995 and 2000, which corresponds to motions over a range of about 50 km s$^{-1}$. Based on the high-velocity, blueshifted emission lines, they further suggested that H$\text{H}$ 208 is moving almost directly at us, rather than being connected to 154–240. In our data, knot A is the most extreme position, being beyond our grid of C-shock models. It is certainly higher velocity than any other H$\text{H}$ 208 location, but it may be either a high-density ($>10^7$ cm$^{-3}$) J-shock or a low-density ($<10^4$ cm$^{-3}$) C-shock. The position of knot B, serving as a bridge between knot A and the rest of the object, is suggestive of a relationship between the forbidden-line and H$_2$ emission. At 42 km s$^{-1}$ and 10$^{4.5}$ cm$^{-3}$, knot B has the second lowest density after knot U.

The arrangement of knots D-E-P-N-J-F (Figure 11) is suggestive of the “ring” that Schild et al. (1997) pointed out in the northeastern edge of the Orion H$_2$ emission. The H$\text{H}$ 208 knots have deduced shock parameters in the 27–40 km s$^{-1}$ and 10$^{4.5}$–10$^{5.2}$ cm$^{-3}$ ranges, with no clear pattern. However, there may be some excitation gradient with distance from knot B. Around knots B-D-E in Figure 11, the purple features show where the H$_2$ and Fe $\pi$ emission coincide, and the purple disappears beyond...
knot E. Since forbidden-line emission arises from fast J-shocks, in these regions at least, the spatial coincidence of H$_2$ and Fe ii emission may be inconsistent with our general result that the H$_2$ emission in HH 208 arises in C-shocks. The knot of high-velocity S ii emission designated HH 208NNW by O’Dell et al. (1997a) corresponds to the Fe ii emission we find accompanying H$_2$ knots D-E-F; this emission can also be seen in combined S ii and O i emission in Figure 2 of O’Dell et al. (1997b). Further away, knots J and N together form object 11 of Chrysostomou et al. (1997), one of the regions from which they detected discrete high-velocity H$_2$ emission. Knot P shows neither forbidden-line emission nor high-velocity H$_2$ emission.

Knots R and U together form HH 208NW (O’Dell et al. 1997a). Knot R shows optical forbidden-line emission, including high-velocity, blueshifted S ii emission (O’Dell et al. 1997a). The motion of knot R (129°–216°) in the plane of the sky is 49 km s$^{-1}$ and of knot U (126°–214°) is 65 km s$^{-1}$ (Doi et al. 2002), both roughly to the west on a path that would have recently traversed the B-D-E-N-J-F ring. These proper motions put both these objects in the vicinity of BN/1/n around 1000 yr ago (Doi et al. 2002), consistent with many other H$_2$ features in the BN region but significantly earlier than the 500 yr old BN/1/n breakup (Rodríguez et al. 2005; Gómez et al. 2005). In our data knot R shows the highest preshock density (10$^{5.5}$ cm$^{-3}$) but the lowest shock velocity (26 km s$^{-1}$) in HH 208, suggesting the H$_2$ is not in the same region which produces the high-velocity S ii emission. Knot U ties with knot B for the second highest velocity (42 km s$^{-1}$) and has the lowest density (10$^{4.0}$ cm$^{-3}$). Although they may be unrelated to the B-D-E-N-J-F ring, knot U (or perhaps knot R) may be faster-moving material—a wind or knot—that impacted the ambient medium to create the ring. Knot A could be a faster-moving section of the expanding ring, which is moving toward us. The ambient material would then have been a local H$_2$ clump or even the core of a single, low-mass star-forming region.

4.2.2. 159–242 and 161–246

Objects 159–242 and 161–246, in the southwestern lobe of the outflow, are part of OMC peak 2 (Beckwith et al. 1978). Gustafsson et al. (2003) found that 159–242 (their object 6) has a peak velocity of +11 km s$^{-1}$ and 161–246 (the western half of this knot is their object 19) has a peak velocity of −15 km s$^{-1}$. Applying shock models to their 2.12 μm 1−0 S(1) flux measurements, Vannier et al. (2001) derived a preshock density of 10$^{4}$ cm$^{-3}$, yielding a mass in 161–246 of 0.1–0.15 $M_\odot$, making it the most massive clump in their field. This led them to suggest that the clump is a candidate site for low-mass star formation. Kristensen et al. (2003) expanded on that work by including 2−1 S(1) images; revising their shock models in light of the new data led them to conclude that the density is an order of magnitude greater than Vannier et al. (2001) calculated. Kristensen et al. (2003) also concluded that the 2−1 S(1)/1−0 S(1) flux ratio included a contribution due to radiative excitation from $^3\Pi$ C Ori, as well as shocks. They were unable to reproduce both brightness and line ratios with a single type of shock, and therefore they suggested that the shock contribution to the emission is composed of C-shocks in the interior of the clump, with J-shocks on the exterior. Our H$_2$ emission is shown in Figure 10. From our analysis, 159–242 and 161–246 are well fit by shock velocities of 41 and 42 km s$^{-1}$ and much lower preshock densities of 10$^{4.5}$ and 10$^{4.4}$ cm$^{-3}$. This suggests that the material producing the 2.12 μm 1−0 S(1) emission is insufficient to support even low-mass star formation. We do find that the line ratio is about 50% higher in a small region 0.9° east of the maximum H$_2$ emission in 159–242, implying a higher shock velocity and lower density there, consistent with the exterior J-shock proposed by Kristensen et al. (2003).

5. SUMMARY

From 0.2° (90 AU) angular resolution HST NICMOS narrow-band images of OMC-1, which resolve individual shocks, we estimate the brightnesses of H$_2$ transitions at 1.89 and 2.12 μm for 23 features. A comparison of the data with shock models shows that most of the data cannot be fitted by J-shocks but are well matched by C-shocks with shock velocities in the range of 20–45 km s$^{-1}$ and preshock densities of 10$^{4}$–10$^{6}$ cm$^{-3}$. The narrow range of shock velocities is not surprising, since both slower C-shocks and faster J-shocks produce weaker H$_2$ emission and would not have been detected. Although there are many shock features in the OMC-1 region, most of the features appear to be well-characterized by a limited range of shock velocities and preshock densities, supporting the possibility of a common origin. In addition, these values confirm the findings of larger beam studies, which averaged over a number of individual shocks. Two objects, 143–239 and HH 208A, are possibly due to J-shocks, and the former does coincide with a known water maser. Optical forbidden-line measurements of some features in HH 208 require fast J-shocks for excitation; we cannot explain this apparent discrepancy.

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