OBSERVATIONS OF SHOCK WAVES IN INTERSTELLAR CLOUDS

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Abstract: Some techniques for observing shock waves in interstellar clouds are discussed. It is concluded that recent measurements of molecular hydrogen emission provide the best currently available technique for studying shocks. The results of measurements toward the Orion nebula are discussed, and a discussion and summary of the currently known H_2 sources is given.

Shock waves have been recognized as important components of the interstellar medium for many years, a recognition which extends to their presence in molecular clouds (see, e.g., Field et al. 1968). Supersonic gas flows driven by cloud collisions, stellar winds, supernova explosions result in the turbulent heating of these clouds through shock waves. Several theories of sequential star formation rely heavily on shock waves to trigger gravitational collapse (Elmegreen and Lada 1977, Gerola and Seiden 1978, and others), and shocks are considered crucial to the development of spiral structure in galaxies.

Unambiguous observational evidence for shocks in molecular clouds has emerged rather slowly, however, primarily because of ambiguity in the available measurements and limited instrumental sensitivity at infrared wavelengths where most of the radiation is expected.

For some strong shocks such as those proposed to explain Herbig-Haro objects (Schwartz 1975, 1978), easily observable optical lines are excited, but, unfortunately, these lines are not unique to interstellar shock waves. Spitzer and Cochran (1973) found rather high rotational temperatures ∿ 1000 K for molecular hydrogen in their ultraviolet absorption line measurements, which Spitzer and Morton (1976) attribute to line of sight gas heated by interstellar shock waves. Their observational technique prohibits mapping, so the extent and power of the shocks has not yet been determined. These observations suffer the additional problem of heavily blended line profiles for the

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different shock components hampering line width analysis. Similar studies of intermediate velocity gas (50 to 100 km s^{-1}) have been carried out which indicate shocked gas in low density regions (see Shull 1977; Cowie et al. 1979, and references therein).

Several workers have taken a different approach by gathering indirect evidence for shock waves with observations of abrupt velocity changes in CO (Lada et al. 1978, Elmegreen and Moran 1979), NH_3 (Ho and Barrett 1978), and neutral hydrogen and OH line profiles (De Noyer 1978, 1979). Most of these observations are ambiguous as regards shocks, since line of sight velocity discontinuities only suggest the existence of shock waves. De Noyer's work is the most conclusive of these studies. Her velocity data demonstrate the existence of shocked gas which has been confirmed by the detection of molecular hydrogen emission (Treffers 1979).

The discovery of emission from vibrationally excited molecular hydrogen by Gautier et al. (1976) was the first detection of lines which are probably unique to interstellar shocks. Calculations by Hollenbach and Shull (1977); Kwan (1977); and London, McCray, and Chu (1977) show these lines can provide the dominant radiative cooling for interstellar shocks at a variety of densities and shock velocities. The relevant vibrational states are difficult to excite in great quantities by other means, so the H_2 lines are a signature of shock-heated molecules. Aannestad's (1973) calculations indicate that lines at 6.9 and 9.7μm from rotationally excited molecular hydrogen and a fine structure line at 63μm from neutral oxygen are equally important for shocks under different density conditions. The 63μm line has recently been detected in Orion by Melnick, Gull, and Harwit (1979) and by Storey, Watson, and Townes (1979), and the rotational lines of H_2 are being actively pursued by at least two groups. Kwan (1977) notes the probably importance of CO transitions between highly excited rotational states ($J \sim 22$) to radiative cooling of weak shocks, but instrumental sensitivities are orders of magnitude away from those required to detect these lines. The near infrared observational techniques have, however, progressed to a stage where measurements of shock waves in molecular clouds can be made routinely.

Measurements of molecular hydrogen emission provide the most sensitive currently available technique for directly observing shocked gas in molecular clouds. In the following two sections we review the results of the recent observations of this emission and place them in perspective as they relate to interstellar shocks. The Orion observations are by far the most extensive, so Orion is treated separately in the first section, and observations of other H_2 emission sources are discussed in the second section. Ironically, the most recent data on Orion has shed doubt upon the shock wave interpretation where the supportive arguments have previously been the strongest. Nonetheless, the theoretical considerations still argue strongly that shock heating is the most plausible means of exciting large quantities of hydrogen molecules, so, with an eye to the future, we will discuss the H_2 sources in terms of shock excitation.

1. MOLECULAR HYDROGEN EMISSION FROM THE ORION MOLECULAR CLOUD

The original measurements of Gautier et al. (1976) showed level populations for the v = 1; J = 1,2,3, and 4 levels consistent with thermal equilibrium at a temperature between 1000 and 3000 K. More refined measurements which include the v = 2, J = 3 level and corrections for line of sight reddening indicate level populations in thermal equilibrium at a temperature of 1900±300 K. (Beckwith et al. 1978b; Beckwith, Persson, and Neugebauer 1979). Typical H_2 column densities derived from the observations are $\sim 3\times10^{20}\ \mathrm{cm}^{-2}$ assuming complete thermal equilibrium at 2000 K.

Maps by Grasdalen and Joyce (1976) and Beckwith et al. (1978b) show the molecular hydrogen emission comes from a spatially extended region, roughly 1 arc minute (0.15 pc) in diameter. The reddening measurements of Beckwith, Persson, and Neugebauer (1979) and Simon et al. (1979) indicate that the emission region is within the cloud at depths comparable to those of BN and KL. If volume densities inferred from observations of other molecules of $\sim 10^6\ \mathrm{cm}^{-3}$ apply to the H_2 emission region, the observed H_2 column densities of $\sim 3\times10^{20}\ \mathrm{cm}^{-2}$ imply a line of sight extent of 10^{-4} pc for the hot molecular hydrogen. Hollenbach and Shull (1977); Kwan (1977); and London, McCray, and Chu (1977) show the observations result naturally if a shock wave with a velocity between 10 and 25 km s^{-1} moves into the ambient cloud where the density is greater than $\sim 10^7\ \mathrm{cm}^{-3}$. The larger velocity limit is necessary so that shock does not dissociate all the hydrogen molecules upon passage (Kwan 1977).

Nadeau and Geballe (1979) obtained profiles of the v = 1 → 0 S(1) line which indicate velocities substantially greater than 25 km s^{-1}. Line widths as large as 60 km s^{-1} and blue-shifted wings moving at 90 km s^{-1} relative to the ambient molecular cloud are seen in their spectra. These observations invalidate the interpretation that a single shock wave with a velocity less than 25 km s^{-1} excites the H_2. Indeed, the profiles strongly suggest the molecular hydrogen is excited in a region with a line of sight extent comparable to its projected size undergoing differential expansion, not in a very thin region immediately behind a shock discontinuity. The shock calculations referenced above do not readily account for these observations.

The evidence nonetheless indicates some kind of shock excitation is responsible for the molecular hydrogen emission. The H_2 appears to be thermalized at 2000 K, whereas CO observations show the vast majority of the gas in this region is at less than 100 K (Zuckerman, Kuiper, and Rodriguez-Kuiper (1976; Kwan and Scoville 1976; Phillips et al. 1977) indicating thin regions of hot gas embedded in the molecular cloud.

The extreme velocities seen in the line profiles almost certainly imply the existence of strong shock waves in the cloud in any case. The failure of the calculations to account for all the observations probably results in part from complicated geometrical effects within the gas flows and in part from inaccuracies in the calculations themselves. For example, shocks arising from turbulence within a region of expanding gas might excite H_2. The shock speeds may be less than 25 km^{-1} relative to the gas, but they appear to be larger due to the expansion. A second point has been raised by Hollenbach and McKee (1979). A strong shock wave may dissociate all the hydrogen molecules it encounters which then recombine on grains behind the shock and become thermalized at 2000 K. The 25 km s^{-1} upper limit to the shock velocity does not apply to this situation. Finally, the 25 km s^{-1} limit itself may be incorrect. Dalgarno and Roberge (1979) have shown the dissociation rates used to derive the limit may be too high because of quantum mechanical corrections which have to be taken into account at interstellar cloud densities. A calculation using the revised rates might bring the shock theory into parity with the velocity results.

Perhaps the most interesting feature of the molecular hydrogen observations is that they imply the existence of rather extraordinary energy sources within the Orion molecular cloud. If the hydrogen is heated because energy in a systematic gas flow is converted into thermal energy which is then radiated in molecular hydrogen lines, the total luminosity of all the H_2 line radiation provides a lower limit to the rate of conversion. The observed luminosity of molecular hydrogen emission is of order 1000 $L_\odot$ (Beckwith, Persson, and Neugebauer 1979). The 60 km s^{-1} width of the lines implies a typical flow velocity of 30 km s^{-1}. The observed size of the region is 0.2 pc, which implies this phenomena has proceeded for at least 3,000 years and has thus liberated roughly 10^{48} ergs. If the flow is the result of an explosion as suggested by Kwan and Scoville (1976), then the explosion energy is of supernova proportions. If the flow is the result of strong stellar winds as suggested by a variety of authors, then $1/2\ \dot{M}v_w^2$ is $\sim$ 1000 $L_\odot$, where $\dot{M}$ is the mass loss rate and v_w is a velocity characteristic of the wind. Even if $v \approx 100$ km s^{-1}, then $\dot{M} \sim 10^{-3} M_\odot\ yr^{-1}$. This mass loss rate is uncomfortably large.

Several authors have noted that the spatial coincidence and line of sight proximity of the H_2 emission to the BN and KL infrared sources suggest a casual relationship. The observed mass motions may result from a violent ejection of matter or extraordinary stellar wind which is generated by a star during its premain sequence evolution. This possibly emphasizes the importance of observations which clarify these energy arguments. It is equally important to determine how prevalent this phenomenon is among star formation regions. Attempts to discover another H_2 emission region comparable to Orion have failed to yield conclusive results as discussed in the next section, although W3 and NGC 7538 are promising candidates.

2. ADDITIONAL SOURCES OF MOLECULAR HYDROGEN EMISSION

Thirteen objects in addition to Orion are known to exhibit H_2 emission at this time; they are listed in the table. None of these sources has been observed in sufficient detail to infer shock excitation although it has been argued that other suggested excitation processes appear unlikely (Gautier 1978, Beckwith 1978). If we assume the H_2 is shock heated, then we may estimate radiated energies and mass loss rates by analogy to Orion. By assuming an excitation temperature of 2000 K and using the observed H_2 emission intensities and source sizes in the table, the total H_2 luminosities are computed in the fourth column. Taking 20 km s^{-1} to be a typical velocity and using the source size to obtain minimum ages, the total radiated power and mass loss rates are computed in the fifth and sixth columns. The calculated mass loss rates will of course be substantially smaller if larger wind velocities are assumed. Here, we have taken 20 km s^{-1} to be consistent with the shock model of Kwan (1977).

Object	$I(v=1\rightarrow0\ S(1))^a$	Extent pc	Total $L_{H2}{}^b$ ($L_\odot$)	Radiated Energy (ergs)	dM/dt ($M_\odot yr^{-1})^e$	Refs.[f]
Orion	100 $(4000)^c$	0.2	20 $(800)^c$	(5×10^{47})	$(2\times10^{-2})^c$	5,6,15 17,27,32
W 3 $E\&W^d$	2	0.9	25	7×10^{46}	8×10^{-4}	14
NGC 7538^d	3	0.6	6	1×10^{46}	2×10^{-4}	14
NGC 7027	25	0.09	1	3×10^{44}	3×10^{-5}	38
BD +30°3639	7	0.1	0.3	9×10^{43}	$9\ 10^{-6}$	4
Hb 12	7	<0.09	0.2	$<6\times10^{43}$	6×10^{-6}	4
CRL 2688	9	--	--	--	--	4
CRL 618	36	--	--	--	--	4
NGC 6720	2	0.2	0.4	2×10^{44}	1×10^{-5}	4
NGC 2440	2	0.1	0.06	2×10^{43}	2×10^{-6}	2
T Tauri	12	<0.005	0.004	6×10^{40}	1×10^{-7}	3
LkHα 349^4	3	0.3	1	9×10^{44}	3×10^{-5}	14
IC 443	10	--	--	--	--	37
NGC 1068	6	<900	3×10^6	$<8\times10^{54}$	9×10^1	36

[a] Normalized to average Orion brightness.

[b] Total L_{H2} = 7.6 L(v=1→0 S(1)) for an assumed temperature of 2000 K.

[c] Numbers in parentheses have been corrected for extinction.

[d] Preliminary results pending confirmation.

[e] Assumes v_w = 20 km s^{-1}.

[f] Numbers refer to order of reference in bibliography.

The molecular cloud sources W3 and NGC 7538 may be roughly comparable to Orion in apparent H_2 luminosity, although these sources need confirmation. Because only measurements of the v = 1→0 S(1) line exist, it is impossible to determine their actual luminosities and flow velocities, so detailed comparison must await more extensive observations. On the basis of the apparent luminosities, however, it appears the internal turmoil of the Orion source may be a fairly common property of star formation regions within molecular clouds. The total energies and mass loss rates estimated for the planetary nebulae compare favorably with source kinetic energies estimated by other means. For example, typical kinetic energies of the expanding nebulae are $\sim 10^{44}$ ergs. The mass loss rate inferred for T Tauri is similar to estimates of the mass loss rates by the visual spectroscopic measurements of Kuhi (1964). It is interesting to note, however, that Ulrich (1976) accounts for Kuhi's measurements with a mass infall model. Molecular hydrogen observations may help resolve this controversy when the excitation process is understood.

NGC 1068 is the most surprising source among this sample. Roughly 10^5 clouds each with the apparent H_2 luminosity of Orion are required to explain the observed emission in NGC 1068. While the Orion phenomena may occur commonly in molecular clouds, the required number is nonetheless large, and indicates that a considerable amount of turbulent energy is deposited in the molecular medium within this Seyfert galaxy.

We stress that these conclusions are based on the assumption of collisional excitation of the observed molecular hydrogen. Further observations are needed to verify this assumption for the emission sources listed in the table.

3. SUMMARY

A variety of recent observations provide evidence for the existence of shock waves within molecular clouds. Of the available techniques, observations of near infrared emission from molecular hydrogen are currently the most promising for direct observations of the shocked gas. The temperature, extent, and velocity of the gas may be obtained in a straightforward manner from these observations.

Observations of molecular hydrogen emission from the Orion molecular cloud have pointed out sources of kinetic energy of unexpected proportions. These conclusions are consistent with but entirely independent of similar conclusions inferred from measurements of CO emission (Zuckerman, Kuiper, and Rodriguez Kuiper 1976; Kwan and Scoville 1976; Phillips *et al*. 1977).

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DISCUSSION FOLLOWING BECKWITH

Elmegreen: The excited H_2 emission may not originate deep inside the Orion cloud even though the extinction is high: 40 magnitudes of extinction at a density of $10^6 cm^{-3}$ corresponds to a physical depth of only 0.01 pc. In fact, all of the recent star-forming activity in the KL region may be close to the cloud's interface with the Orion Nebula, as if the expansion of this visible nebula directly induced the star formation by compression and gravitational collapse.

Beckwith: Your point is certainly well taken. On the other hand, the total extinction through OMC 1 is estimated from other molecules to be around 200 magnitudes so 40 magnitudes implies a depth $\sim 1/5$ of the total cloud diameter. This distance is much greater than 0.01 pc.

Elmegreen: These shock diagnostics may eventually play an important role as an indirect probe of magnetic field dynamics. If, for example, velocity jumps are seen in the cold molecular emission at locations adjacent to known sources of pressure (bright rims, etc.), and these velocity jumps are less than or equal to the cloud's linewidth, then it is possible that a high temperature shock will not occur (even though the velocity jump may be greater than the gas sound speed) because the compression will propagate into the cloud at speeds less than the Alfvén velocity. This situation may be common near those parts of an HII region where expansion is occurring in a direction perpendicular to the cloud's embedded magnetic field.

Lortet: In your computations of stellar wind, you find a mass loss that is very large indeed ($10^{-3} M_\odot$ yr^{-1}) because you take a very low velocity for the wind ($V_w \approx 100$ km s^{-1}). Why did you choose so low a velocity?

Beckwith: Most of the energy in the wind is deposited in the H_2, and the wind velocity was simply chosen to equal the highest observed H_2 velocity. Certainly a higher wind velocity will considerably lower the mass loss rate. However, to keep the loss rate low, there has to be a very efficient mechanism for converting the wind energy into the energy radiated by the H_2 molecules. It may be difficult to make such a model consistent with all observations of this region.

Elitzur: Can a velocity of 100 km s^{-1} and H_2 rotation-emission both be accommodated without dissociation occurring?

Beckwith: This problem is probably the most difficult we face in explaining the H_2 emission as shocked gas. It is possible that the shocks are actually propagating at a velocity <25 km s^{-1} relative to an outflowing wind or expanding envelope which has a very high velocity relative to us. It may be that all the H_2 molecules have been dissociated by a fast shock, and we observe H_2 which has reformed behind the shock (Hollenbach and McKee, Ap. J. Suppl., October 1979). At present we cannot distinguish between these possibilities, and no other suggestions have yet been made.

Clark: Orion shows evidence of large amounts of angular momentum down to scales of $\sim$1 arcmin. Your H_2 map shows H_2 emission decidedly in the *polar* direction. Could a possible explanation involve gravitational infall along the rotational pole, perhaps coupled with a stellar wind, all "meeting", so to speak, at the "centrifugal" barrier? Such an explanation may be consistent with all available data, and would provide a natural anisotropy for the shock.

Beckwith: We have attempted to construct models invoking gravitational collapse, but we find the core masses needed in these models to be implausibly high, of order 10^4 $M_\odot$.

Carruthers: Have searches been made for H_2 emission from supernova remnants in highly obscured regions such as Cas A?

Beckwith: Some searches have been made, particularly in IC 443. There have been few sensitive searches toward other supernova remnants, including Cas A.