THE IMPLICATIONS OF MOLECULAR HYDROGEN EMISSION

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Abstract: Emission from vibrationally excited molecular hydrogen has been discovered in a variety of objects of widely differing ages and environs including molecular clouds, planetary nebulae, and a Seyfert galaxy. The observations of the H_2 spectra indicate this emission arises in hot, nearly thermalized gas. While there is still some disagreement between detailed predictions of hydrodynamic calculations and recent observations, it is generally believed that energy supplied to the interstellar gas in the form of shock waves is responsible for the observed H_2 emission.

Several of the H_2 sources are molecular clouds associated with ongoing star formation, most notably the Orion Molecular Cloud. From the intensity, strength, temperature, and velocity of the molecular hydrogen emission, it is estimated that at least 10^{48} ergs has been deposited in the cloud over the last thousand years or so in the form of bulk kinetic energy. There is no clear explanation for this process, since the energy is large and the timescale short, and it appears unlikely that we should observe such events unless they occur frequently. Among the other H_2 sources in molecular clouds, NGC 7538, DR 21, and W3 are of similar spatial extent and apparent luminosity as the Orion emission.

1. INTRODUCTION

When Gautier, Treffers, and their collaborators (Gautier et al. 1976, Treffers et al. 1976) discovered vibrationally excited molecular hydrogen in the Orion molecular cloud and in NGC 7027, they uncovered a component of interstellar gas which was almost completely unanticipated by earlier molecular observations. This component consists of dense interstellar material, primarily molecular hydrogen, which has been heated to several thousand degrees, and it contrasts with the more commonly observed molecules which indicate dense molecular gas at a few tens of degrees. The hot gas is widely believed to result from shock waves in the clouds. The unusual strength of the H_2 lines, indicating very energetic shocks, has been a surprise. Prior to the

C. G. Wynn-Williams and D. P. Cruikshank (eds.), Infrared Astronomy, 167–178.

discovery of H_2 emission and the nearly simultaneous discovery of high-velocity CO line wings, millimeter line observations showed gas velocities which were typically less than 10 km s^{-1}, not high enough to excite the vibrational lines of molecular hydrogen.

Following the Orion observations, molecular hydrogen emission was detected from a variety of other celestial objects. Beckwith, Persson, and Gatley (1978) observed H_2 toward five more planetary nebulae, and Beckwith et al. (1978a) found H_2 emission from T Tauri. Gautier (1978) discovered spatially extended H_2 emission from several molecular clouds, and, more recently, Fischer and her collaborators (Fischer, Righini-Cohen, and Simon 1980; Fischer et al. 1980) have observed H_2 in two more clouds which are sites of recent star formation. Elias (1980) has measured H_2 emission lines from seven Herbig-Haro objects in a sample of nineteen. In several cases, it can be shown that the H_2 is probably shock-heated as in Orion; in no case can it be shown that the H_2 is excited by any other process.

Several approaches have been taken to understand the implications of this emission. A variety of new lines have been observed in the shocked regions, notably Orion, to determine the structure and physical condition of the gas flows. Surveys are being made to determine the frequency with which molecular shock waves are generated in the interstellar medium. These surveys, although difficult, now suggest gas flows are relatively common in a variety of celestial objects. The analyses of those objects which show H_2 emission indicate that in some objects (for example NGC 7027), the shocked gas can be easily explained with known gas flows, whereas in others (for example Orion), it is difficult to identify a source which can provide sufficient energy to drive the shock waves. There has been some speculation and considerable controversy about the nature of the source in Orion and its relation to star formation, and it is this problem which is of greatest current interest in the study of H_2 emission.

Theoretical studies of shocked molecular hydrogen have elucidated other aspects of the problem, and the discoveries have stimulated a new interest in the radiative cooling of molecular shocks. The theoretical work of Hollenbach and Shull (1977); Kwan (1977); and London, McCray, and Chu (1977) is essential to the interpretation of the infrared observations. More recent work has gone beyond the H_2 to discuss the direction of new observations. For the sake of brevity, only those calculations which are directly applicable to existing H_2 observations are discussed in this review. The rich literature of other calculations is discussed by Hollenbach (1979) and McKee and Hollenbach (1980).

The following discussion is divided into three sections. The first section (Section 2) described the H_2 emission from the Orion nebula. Orion is the best studied of all the H_2 sources, and it provides a basis for comparison with other H_2 emission regions. The next section summarizes the new results on other H_2 sources. Most of these results have been obtained recently, and only limited data are available for discussion. In the final section, the future of the H_2 observations is briefly discussed.

2. THE ORION MOLECULAR CLOUD

Orion is the best-studied of the known H_2 emission sources. The H_2 emission was first detected by Gautier et al. (1976), and subsequently a wealth of observational information has been obtained by various groups (see, e.g., Grasdalen and Joyce 1976; Beckwith et al. 1978b; Beckwith, Persson, and Neugebauer 1979; Simon et al. 1979; Nadeau and Geballe 1979; Beck, Lacy, and Geballe 1979). Many different molecular hydrogen transitions have been observed in Orion. Because the molecule is homonuclear, all the transitions are electric quadrapole, and every line observed is optically thin with optical depths typically less than 10^{-4}. Thus, from the observations of the vibrational transitions, the excitation temperature, column densities, and extinction can be derived in a self-consistent way.

The relative level populations indicate a region in approximate thermal equilibrium at a temperature of 2000 K; the column density of this gas is of order 3×10^{20} cm^{-2} which is only a small fraction (<1%) of the total H_2 column density in the cloud estimated from other molecular lines. The emission region extends over an area roughly 0.2 pc across, and it is inside the molecular cloud as indicated by the 40 visual magnitudes of extinction to the emission region (see Beckwith, Persson, and Neugebauer, 1979, for a more detailed discussion). There is also H_2 emission which arises from a somewhat cooler ($\lesssim$ 1000 K) region with greater column density (Beck, Lacy, and Geballe 1979). The linewidths vary from 60 km s^{-1} FWHM with wings extending to over 90 km s^{-1} from the line centers in spectra taken near the center of the emission region to less than 30 km s^{-1} FWHM in spectra taken near the edges (Nadeau and Geballe 1979). The line centers are at 9 km s^{-1} (LSR) identical to the line centers of the radio molecular lines to within the observational uncertainties.

The temperature and velocity of the H_2 contrast sharply with most of the molecular material along the line of sight. As inferred from several molecules, notably CO, most of the gas is less than 100 K, with linewidths less than 10 km s^{-1} centered on 9 km s^{-1} LSR, and total column densities of order 10^{23} cm^{-1} or more (Zuckerman 1973). The H_2 emission thus indicates that a small fraction of this gas is quite hot and moving with supersonic velocity relative to the main cloud. Yet the apparent spatial extent of the hot H_2, $\sim$ 0.2 pc, is comparable to the extent of the cloud core, $\sim$ 1 pc. Although only a small fraction of the total molecular material in the core is hot at any time, a much larger fraction has probably been through a hot phase as the hot region grew to its present size.

Most of these observations are readily explained by assuming the H_2 is heated by shock waves driven into the molecular cloud by supersonic gas flows. The calculations of Hollenbach and Shull (1977); Kwan (1977); and London, McCray and Chu (1977) show that shocks should produce the observed column densities of molecular hydrogen at 2000 K if the ambient volume density is of order 10^7 cm^{-3} and the shock velocities range between 10 and 25 km s^{-1} . The required volume densities while high are consistent with other molecular density indicators. Furthermore, several of the most recent observations were anticipated by the first calculations such as the existence of a cooler post-shock region studied by Beck and her collaborators and the CO emission from high-rotational states ($J \sim 25$) studied by Storey et al. (1980). The observed velocities, however, are outside of the range allowed by the theory, the range of shock velocities being limited on the high end by the speed at which all the H_2 molecules are dissociated by the shock. While there has been some dispute about the exact value of this speed (e.g. Dalgarno and Roberge 1979), it is probably not far in error at the derived densities. Since this velocity is less than the observed velocity of much of the H_2, there has been some effort to bring the theory into parity with the observations (e.g. Hollenbach and McKee 1979, Kwan 1979, Draine, Roberge, and Dalgarno 1979, Chevalier 1980). None of these explanations has gained widespread acceptance, but it is generally assumed that some kind of shock-heating excites the H_2, and since we expect shocks to occur anyway from the supersonic velocities indicated by the extreme H_2 line wings, we will assume the H_2 is shock-excited.

Simultaneous with the discovery of the H_2 emission, the CO line profiles in the direction of the cloud core were shown to exhibit wings extending beyond ±50 km s^{-1} (Zuckerman, Kuiper, and Rodriguez-Kuiper 1976; Kwan and Scoville 1976). The flows which produce these velocities are presumably connected with the flows which produce the H_2 emission. There are now a variety of observations of various molecules such as CO, H_2O, and NH_3 which probe various aspects of these flows (see for example Phillips et al. 1977, Wilson et al. 1979, Genzel et al. 1980, and Storey et al. 1980). Gas flows of this type described above have rather remarkable implications for the energetics of the cloud core. Simple dimensional arguments based on either the H_2 or CO observations indicate the kinetic energy input to the cloud per unit time must be large, and the momentum input per unit time is greater than can be obtained from simple radiation pressure models by a factor of a hundred to a thousand, depending on the assumptions. The gas flows thus appear to be caused by a process such as mass loss (with extraordinary mass-loss rates) or an explosion (of energies near those of supernovae), presumably associated with star formation in the cloud core.

If we assume the typical flow velocity is 30 km s^{-1} and the radius of the flow region is 0.1 pc, then the time for the region to expand to its observed size at this velocity is about 3,000 years. For explosions or winds where the overall velocity is a decreasing function of time, this is an upper limit. The total luminosity of the H_2 emission is of order 1000 $L_\odot$, so if this emission has proceeded for the expansion time, then about 3×10^{47} ergs have been radiated. Isothermal shock waves radiate energy at about the same rate as they deposit bulk kinetic energy in a flow, so we might expect that the expanding gas now contains a few times 10^{47} ergs of kinetic energy. This estimate gives almost the same result as estimates of the kinetic energy, based on CO observations (Zuckerman, Kuiper, and Rodriguez-Kuiper 1976; Kwan and Scoville 1976). The momentum in the flow can be estimated in a similar fashion to be roughly 10^{41} g cm s^{-1}. For comparison, the total energy radiated by the infrared cluster in 3,000 years is a few times 10^{49} ergs. The total momentum which is transferred to the gas through radiation pressure is $(\tau\ L/c)\ t = 10^{39}\ \tau$ g cm s^{-1}. The factor τ is essentially the number of times a typical photon is absorbed or scattered before escaping the expanding gas. Notice that this estimate is based on the total luminosity, size, and velocity of the H_2.

These estimates show that while the kinetic energy in the gas is only 1% of the energy radiated by the infrared cluster over lifetime of the flow, the total momentum is unusually large. If the gas is driven by radiation pressure only, the factor τ must be at least 100 in the equation above. Kwan and Scoville (1976) suggested a supernova may have exploded within the cloud less than 1000 years ago and caused an expansion of the cloud core. Other authors (e.g. Genzel and Downes 1977) have favored mass loss from a star or stars in the infrared cluster as the energy input; the mass-loss rates required are of order $10^{-4}\ M_{\odot}\ yr^{-1}$ or more, in the simplest models (Beckwith 1979). Neither supernovae nor objects with such high mass-loss rates were supposed to exist within the Orion molecular cloud prior to these observations. These observations have thus added two new pieces to the puzzle of star formation. They suggest that some short-lived energetic object is associated with at least one well-studied star forming region, and they show that the structure of the core immediately surrounding a premain-sequence association may be swept clean by one of the members of the association. The expansion time of less than 3000 years is perhaps the most striking feature of these remarks. The a priori probability that we should observe such a short-lived phenomenon is small unless the phenomenon occurs frequently.

3. SOURCES OF MOLECULAR HYDROGEN EMISSION

Molecular hydrogen emission has been observed from a variety of celestial objects including molecular clouds, planetary nebulae, Herbig-Haro objects, T Tauri stars, supernova remnants, and even the nucleus of a Seyfert galaxy. The spatial extent and luminosity of the H_2 emission varies by several orders of magnitude within the sample. The observations of each different type of object have been interpreted assuming shock-heating.

Since the 1979 review of these sources (Beckwith 1979), three significant results have been obtained. First, Fischer, Righini-Cohen, and Simon (1980) have discovered two more examples of the Orion phenomena in DR 21 and OMC 2. Additionally, Fischer et al. (1980) have re-examined the molecular hydrogen emission in NGC 7538, discovered by Gautier (1978), and support Gautier's suggestion that NGC 7538 is an example of the Orion phenomenon. Second, Elias (1980) has discovered H_2 emission from seven Herbig-Haro objects in a sample of nineteen. Shock waves have been suggested to explain earlier optical line observations of these objects, and Elias suggests his H_2 observations may be explained by shock-heated gas as well. Third, Beckwith et al. (1980) have extended the observations of NGC 7027, and they conclude that the H_2 may be heated at the outer boundary of the ionized gas by a shock wave driven by the expanding nebula. This contrasts with the earlier interpretation that the H_2 planetaries are excited in neutral clumps embedded in ionized gas (Beckwith, Persson, and Gatley 1978).

The molecular clouds contain the most extended and luminous H_2 emission of all these sources. DR 21 and NGC 7538 have apparent H_2 luminosities which are comparable to Orion. In both objects, the molecular hydrogen emission is of lower surface brightness and greater extent than the Orion emission. The arguments of the last section show that if the flow velocities in these objects are of order 50 km s^{-1}, or less, then these emission regions are older, but have total energy contents which are similar to Orion. The theoretical work mentioned earlier places a lower limit of about 10 km s^{-1} to the speed at which a shock wave can excite appreciable amounts of molecular hydrogen. An upper limit on the age of these new sources is the size divided by 10 km s^{-1}, or 10^5 years for the largest region, DR 21. Similar conclusions were reached by Gautier about W3 and S140. In all of these regions, the total continuum luminosity is of order 10^5 $L_\odot$. Therefore, the arguments concerning stellar wind power or explosive energy needed to cause the events in Orion may be applied to the newly discovered H_2 sources. Note that since the extinction has not yet been measured to the newest H_2 sources, these arguments are based only on apparent surface brightness.

Perhaps the most remarkable discovery is the observation of molecular hydrogen emission from NGC 1068 by Thompson, Lebofsky, and Rieke (1978), recently confirmed by Scoville et al. (1980). A crude estimate of the percentage of molecular clouds which contain H_2 emission sources of similar luminosity as the Orion source can be made from this observation. If we assume the total luminosity of a typical molecular cloud is the same as Orion, 2×10^5 $L_\odot$ (Werner et al. 1976), then an upper limit to the number of such clouds is obtained by dividing the total luminosity of NGC 1068, 3.7×10^{11} $L_\odot$ (Telesco, Harper, and Loewenstein 1976), by this luminosity. The limit is $(N_{clouds})\leq2\times10^6$. The same calculation applied to H_2 emission only, where the apparent luminosities of the v = 1→0 S(1) line in NGC 1068 and Orion are 3.5×10^6 and 2.5 $L_\odot$, respectively, implies that 1.5×10^6 clouds exhibit molecular hydrogen at the same strength as Orion. Thus, almost every cloud is a strong H_2 emitter! While this calculation depends upon questionable assumptions, it is difficult to escape the conclusion that a substantial amount of the molecular gas in NGC 1068 has undergone shock-heating. When better statistics become available on sources in our own galaxy, it will be possible to estimate the rate at which energy is deposited in molecular clouds by these gas flows.

Herbig-Haro objects and the star T Tauri are the other premainsequence objects which exhibit H_2 emission (Elias 1980, Beckwith et al. 1978a). The emission from the HH objects has a similar excitation temperature to Orion. Elias notes the linewidths in these objects are probably large, based on the intensity variations of the Q branch, as they are attenuated by the telluric observation. Shocks have been suggested by Schwartz (1978) to explain the optical lines, and the H_2 emission is consistent with this picture. While the observations of the H_2 in T Tauri are limited to the v = 1→0 S(1) line, plausible assumptions about the emission show it can arise from shocks driven by a stellar wind from T Tauri. There is some controversy about the existence of such a wind, however (Kuhi 1964, Ulrich 1976).

Planetary and protoplanetary nebulae have been shown to display H_2 emission. Because the H_2 emission from NGC 6720 showed good spatial correlation with the 6300 Å line of [OI], Beckwith, Persson, and Gatley (1978) suggested the H_2 in planetaries is excited in neutral clumps embedded in the ionized nebula; this interpretation was given by Capriotti (1973) to explain the [OI] emission. Recently, Beckwith et al. (1980) have analyzed observations of the H_2 emission from NGC 7027, and on the basis of the spatial distribution and line intensity ratios they conclude the H_2 is excited by a shock wave at the outer boundary of the ionized nebula. At this time, it is not known if shock waves excite the H_2 emission seen in all planetaries or if some other excitation process is responsible (e.g. Black 1978). Measurements of the H_2 vibrational temperature can in principle answer this question as they have in Orion. If the H_2 seen in planetaries is shock-heated, planetaries should be good examples for a comparison of the theoretical predictions of shock-wave calculations with observations, since the planetaries are geometrically simple and the gas flows can be mapped with a variety of spectroscopic techniques. A crude estimate of the H_2 mass in NGC 7027 based on the H_2 luminosity gives a value of 1 to 4 $M_\odot$. This value is higher than estimates of the mass of ionized matter for NGC 7027 and for most planetaries.

Finally, molecular hydrogen emission has been detected in the supernova remnant IC 443 by Treffers (1979). In this case, shock waves had been detected by DeNoyer (1979a, 1979b) on the basis of her observations of the OH and HI velocity profiles around the source. Beckwith and DeNoyer (1981) show this emission to be extended and roughly cospatial with the CO emission with a temperature less than about 4000 K.

The sample of known H_2 sources is limited primarily by sensitivity, since sensitive searches over large areas are exceedingly time-consuming with existing instrumentation. For example, Scoville et al. (1979) were unable to find H_2 emission from ten southern hemisphere objects, in spite of diligent effort. On the other hand, Gautier and Fischer and her collaborators have found molecular hydrogen emission by searching large areas for extended emission of low-surface brightness. This emission often bears no obvious spatial relationship to other molecular or infrared emission (e.g. Fischer, Righini-Cohen, and Simon 1980) thus compounding the search problem.

4. FUTURE WORK

Perhaps the two most important unresolved issues which come out of this work are the nature of the driving source for the gas flows observed in the molecular clouds, and their overall importance to the collapse of these clouds. At least in the core of Orion, the H_2 and radio molecular line observations indicate turbulent energy is being deposited in the cloud at a high enough rate to affect the line shapes. It will be useful to understand the observed H_2 line intensities in detail from theoretical work to obtain accurate estimates of the energy in the shocks. The overall importance of the phenomena may be assessed by more sensitive surveys of many molecular clouds. As mentioned above, these searches are very time-consuming with available instrumentation, but Gautier and Fischer and her collaborators have already made progress in this important area.

Several groups are searching for other H_2 lines. Beck and her collaborators (Beck, Lacy, and Geballe 1979; Beck *et al*. 1980) have demonstrated the efficacy of measuring the $v = 0$, $J = 4 \rightarrow 2$ line at 12 μm. This line probes a larger, cooler portion of the shocks than the 2 μm lines and, furthermore, should be less susceptible to the extinction which plagues the near-infrared lines. Young and Knacke (1980) have observed the $v = 0$, $J = 11 \rightarrow 9$ line at 4.7 μm; they find significant differences between the observed line intensity and that predicted from the simplest theory. My colleagues and I have recently searched for the $J = 9 \rightarrow 7$, $8 \rightarrow 6$, $7 \rightarrow 5$, and $6 \rightarrow 4$ lines between 5 and 8 μm, specifically to avoid the extinction which complicates the interpretation of the near-infrared spectra. These lines provide additional probes of the shock structure. Hall, Scoville and their collaborators (in preparation) have measured several more H_2 lines from the $v = 2$ state to better determine the vibrational temperature. There are still unexplained differences between the observations and the theory, and it is crucial to extend the observations to other lines if these differences are to be understood.

There has been a long-standing interest in the longer wavelength lines at 28 μm and 89 μm, the latter being very strongly forbidden. These lines have excitation energies which are much less than those of any other mentioned in this article. If these lines can be detected, they may provide us with information about the overall abundance and distribution of molecular hydrogen in the interstellar medium (however, Drapatz and Michel [1974] pose serious doubts about the observability of these lines). Observations at these wavelengths are difficult for a variety of reasons, and it is unlikely these lines will be detected in the near future. Nonetheless, the importance of the results and the unexpected strength of the near-infrared lines emphasizes the need to make these observations whenever it is possible.

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DISCUSSION FOLLOWING PAPER DELIVERED BY S. BECKWITH

BECKMAN: It is important to emphasize that it could well be possible for radiation pressure alone to drive the mass flow (in Orion and similar sources); a factor of 100 is seen to be required in converting photon momentum to mass momentum. The simple formula $h\nu/c$ does not allow for the more efficient coupling of momentum by photons "bouncing around" in a rather opaque shell before their lengthening wavelength allows them to escape.

BECKWITH: That is true; by allowing photons to be multiply reflected you can amplify the momentum you may obtain from them by a factor of τ where τ is the optical depth. The problem is that, for a region like Orion, you need τ to be of order 100 and consequently for the photons to be reflected about 100 times before being absorbed; I know of no models for dust grains which have albedos of 99%.

JOHNSON: Why is it not possible for the molecular gas to be dissociated in the shock and then rapidly recombine on the grains in the high density region? Would not this give a very thin layer of atomic hydrogen for a short time?

BECKWITH: Such a mechanism has, in fact, been suggested by Hollenbach and McKee. A big advantage of the non-dissociating models is that they provide a natural thermostat mechanism which can explain why several of these sources, not just Orion, have H_2 excitation temperatures of 2000 K.

HOLLENBACH: Shocks which dissociate molecules also have a "thermostat" which produces H_2 excitation temperatures of $T \simeq 2000$ K. H_2 molecular abundances are kept low at higher temperatures because of rapid collisional dissociation.

THOMPSON: The maximum H_2 emission does not seem to correlate with the IR maximum in most protostellar sources. Is this true and does it have any physical significance?

BECKWITH: It is true, but the significance is less clear. Part of the explanation is probably that the emission we see is as much dependent on density irregularities in the surrounding medium as on the location of the source of the expanding flow. In any case, we are most sensitive to regions which are quite extended, at which point the distribution of expanding gas may well have lost some of its original symmetry.

T. L. WILSON: What is the upper limit on range of H_2 densities in the shocked gas? Can it be a factor of 10 higher than the 10^5 cm^{-3} you gave as the density required to thermalize the molecular hydrogen?

BECKWITH: Easily. In our original shock models we derived an average density of something like 3×10^7 cm^{-3}, but this, of course, refers only to a very small amount of the gas that has been shocked. To obtain the density in a larger region we need detailed shock models.

HOLLENBACH: I would like to mention that a theoretical problem arises in modeling the 2 μm intensities in Orion as postshock emission. It is difficult to prevent gas phase chemistry from producing so much H_2O that the H_2 emission is quenched by the dominant IR H_2O emission, which cools the gas.

BECKWITH: As techniques improve we ought to be able to see the H_2O vapor lines, and be able to determine exactly how much cooling is going on.

LADA: On the subject of the high velocity wings in the CO lines, I I would comment that similar wings have now been detected in other sources, such as GL 490 and Cepheus A. They are not hard to detect, but were missed in the past because they were not looked for. As you say, these high velocity phenomena are probably common.