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FAST MOLECULAR HYDROGEN FROM TIME-DEPENDENT SHOCKS

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RESUMEN

Es un resultado bien conocido pero enigmático que algunas zonas dentro de las regiones de formación estelar a veces muestran emisión de hidrógeno molecular a muy altas ($\sim 100\,\mathrm{km\,s^{-1}}$) velocidades. Este tipo de observaciones son algo difíciles de explicar porque las ondas de choque tipo salto, no magnetizadas, y de alta velocidad generalmente disocian las moleculas presentes en el medio prechoque y por lo tanto producen muy poca emisión de H_2.

Presentamos modelos en los cuales una onda de choque acelera paulatinamente. Encontramos que, en efecto, tales ondas de choque pueden acelerar masas significativas de material molecular hasta velocidad de $\sim 100\,\mathrm{km\,s^{-1}}$ y son una explicación plausible de la emisión de H_2 de alta velocidad que frecuentemente se observa.

ABSTRACT

It is a well known but puzzling result that zones within star-formation regions sometimes show molecular hydrogen emission at very high ($\sim 100\,\mathrm{km\,s^{-1}}$) velocities. These kinds of observations are somewhat difficult to explain because high-speed, non-magnetized, J-type shock waves mostly dissociate the molecules present in the preshock medium, and therefore produce almost no H_2 emission.

We present models in which a shock wave gradually accelerates. We find that such shock waves are indeed able to accelerate significant masses of molecular material to velocities of $\sim 100\,\mathrm{km\,s^{-1}}$, and are a plausible explanation for the widely observed, high velocity H_2 emission.

Key Words: **ISM: JETS AND OUTFLOWS — STARS: MASS LOSS — STARS: PRE-MAIN SEQUENCE**

1. INTRODUCTION

Over the past decade, it has been found that many of the previously known Herbig-Haro (HH) objects show strong emission in the IR lines of the H_2 molecule with morphologies that many times resemble the distributions of the atomic/ionic optical emission lines (see e.g., Reipurth et al. 1999; Eislöffel, Smith, & Davis 2000). Actually, some of the more remarkable of the so-called "IR jets" that have been discovered do not have (or have very faint) optical counterparts.

The coincidence between the infrared H_2 emission and the optical atomic/ionic emission in the heads of HH jets is somewhat puzzling (see e.g., the observations of HH 32 by Davis et al. 1996 and of HH 7 by Hartigan, Curiel, & Raymond 1989), as the shocks producing the optical emission have shock velocities of $\sim 100\,\mathrm{km\,s^{-1}}$. Such shocks should completely dissociate any H_2 molecules present in the preshock gas, and should not produce any detectable H_2 emission. Even more puzzling is the fact that the H_2 line emission shares the same kinematical properties as the atomic/ionic lines. These results appear to indicate that the atomic/ionic and the molecular emission come from basically the same shock structures, even though the shocks producing the optical emission should, in fact, not be producing a substantial amount of H_2 emission.

The two solutions that have been proposed for this problem are that the H_2 emission could be produced in the magnetic precursor of a J-shock (Hartigan et al. 1989) or in a high-velocity C-shock (Smith & Brand 1990). However, these two options are partially problematic because they require a very low preionization fraction (for the existence of a magnetic precursor) or a quite high magnetic field (for a C-shock transition to occur at high velocities).

It is possible, however, that the observed emission is the result of the interaction between a slowly accelerating outflow and the surrounding, molecular environment. Such an accelerating outflow will have a bowshock with a shock velocity that monotonically increases as a function of time. A similar idea has been applied to wind-driven bubbles by Hartquist & Dyson (1987), in whose model the shock acceleration results from changes in the density of the ambient medium. An accelerating shock will have an early, non-dissociative regime (in the time period during which the shock velocity is $< 50\,\mathrm{km\,s^{-1}}$ or so for the low-density regime), in which the shocked environmental gas is compressed into a dense, molecular layer. At later times (when the shock velocity is $> 50\,\mathrm{km\,s^{-1}}$), the total mass of the molecular layer remains approximately constant (as the new material entering through the shock is no longer molecular), but is accelerated to velocities close to the instantaneous velocity of the shock wave.

2. 1-D MODELS

Since our goal is to study the abundance of H_2 we include a hydrogen-helium chemistry consisting of the following species: H, H^+, H_2, H_2^+, H_3^+, H^-, He, He^+ and HeH^+. These species are linked by a chemical network of 40 reactions. We include these in a one-dimensional hydrodynamic model with the method described above. We impose a reflection condition upon the left-hand boundary of the grid which simulates the application of a "piston" to the gas at this location and thus any disturbance or shock will emanate from this point. Using the definition of force as rate-of-change-of-momentum, the acceleration appears as a source term, F in the momentum equation affecting the momentum per unit mass in all cells equally. In this way the calculation is performed in the non-inertial frame comoving with the acceleration. We accelerate the grid from 0 to $100\,\mathrm{km\,s^{-1}}$, in 1000 yrs, into an environment consisting of the species above in chemical equilibrium at 20 K (this environment is almost completely molecular).

The simulation proceeds as follows: at early times, the shock is non-dissociative with respect to the molecular gas and a layer of shocked H_2 builds up. This simulation is in the low density regime and thus dissociation begins at a shock speed of around $50\,\mathrm{km\,s^{-1}}$ when significant numbers of electrons begin to appear. At this point, the build-up of molecular gas in the post-shock regions stops and a layer of atomic gas appears which helps to shield the molecular layer from the increasingly high temperature gas behind the leading shock. Although there are a number of shock instabilities in the system, this is not the place to describe them in detail as they are not relevant to the build-up of the molecular layer. The deposition of the atomic layer continues indefinitely in the 1-D case, and we continued the simulation for 2000 yrs.

The final (unsteady) situation is shown in Figure 1. In the final configuration, the gas moves through several regimes; moving downstream from the shock front we have the following general zones:

(i) Leading shock and immediate postshock gas. The total number density in this region is $\approx 400\,\mathrm{cm^{-3}}$, and the temperature is $\approx 10^6$ K. Although some ionization of H, radiative cooling and H_2 dissociation takes place in this region the majority occurs in zone (ii).

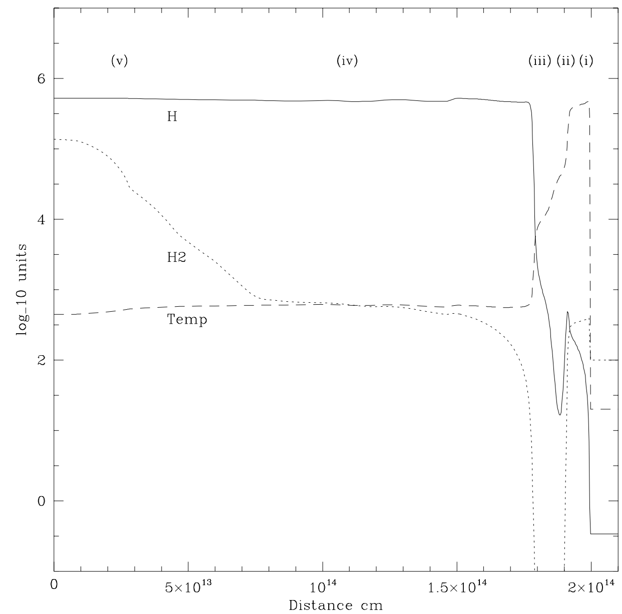

Fig. 1. The 1-D accelerating shock model at a time of 2000 yrs.

(ii) Dissociation layer. This is a very thin layer (10^{11} to 10^{12} cm) in which most of the dissociation and ionization takes place. After these processes the density has risen to $\approx 10^4\mathrm{cm^{-3}}$, and the temperature is $\approx 10^5$ K.

(iii) Strong cooling layer. In this region the gas is dense enough to cool very strongly increasing the density to 10^5 to $10^6\,\mathrm{cm^{-3}}$.

(iv) Neutral H layer. This is composed of quiescent cooled neutral gas which was accumulated by the shock at speeds higher than the critical shock-speed for dissociation of H_2.

(v) Molecular H layer. This material was accumulated prior to the critical shockspeed. This layer is composed almost entirely of molecular hydrogen, it is cool, quiescent and moving with the grid at $100\,\mathrm{km\,s^{-1}}$.

3. 2-D MODELS

Although the 1-D case is quite interesting the high velocity molecular gas observed in star-forming regions is generally seen in jets and their various interactions. We therefore study the case of an accelerating jet. Unfortunately, unlike the 1-D case, we do not have the luxury of being able to accelerate the grid with the jet. The jet must be injected into the grid over a portion of one of the

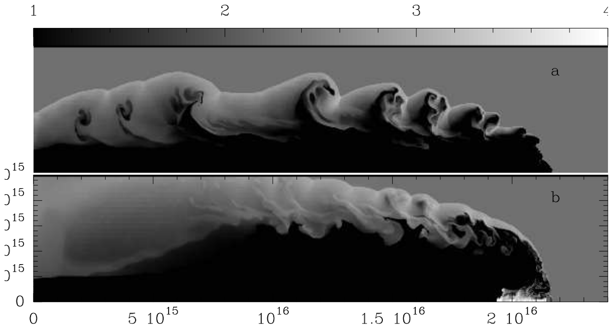

Fig. 2. Number density of H_2 in a steady jet (panel a) and an accelerating jet (panel b).

grid boundaries, the remaining part of that boundary must contain either a reflection condition or a supersonic outflow. If this is not the case, then the solution is not necessarily trustworthy. It may be that we can advect any unphysical waves off the grid during the acceleration process (certainly once the grid is going fast enough this boundary condition should be well-defined). However, the acceleration may cause problems with the jet injection and there will always be a period in which our problem is ill-posed. To be on the safe side, therefore, we keep the grid stationary and impose a linear acceleration of $1\,\mathrm{km\,s^{-1}\,yr^{-1}}$ upon the inflow. At this rate of acceleration the critical shockspeed for H_2 dissociation will be reached at a time of 55 yrs and material at this velocity will reach the head of the jet at about 70 yrs. When the jet speed reaches $100\,\mathrm{km\,s^{-1}}$ it is held constant. In these simulations, we impose a jet radius of 1.0×10^{15} cm, the jet density is $n_{\mathrm{H}} = 4282\,\mathrm{cm^{-3}}$, the environment density is $n_{\mathrm{H_2}} = 288\,\mathrm{cm^{-3}}$, and we include the same H/He chemistry as in the 1-D models.

Figure 2 shows the number density of H_2 in a simulation of this accelerating jet (panel b) and a steady jet simulation with parameters identical to those above but with a constant jet speed of $100\,\mathrm{km\,s^{-1}}$ (panel a). The steady jet is seen to be completely dissociative in H_2 with almost no molecular gas in the stagnation region of the bowshock. By contrast, the accelerating jet shows a region of molecular gas with high density in the stagnation region—this is the remnant of the environmental gas which was swept up by the jet head in the pre-dissociative phase of the jet acceleration. At the point shown in the figure the accelerating jet has been propagating for 140 yrs (cf. 38 yrs for the steady

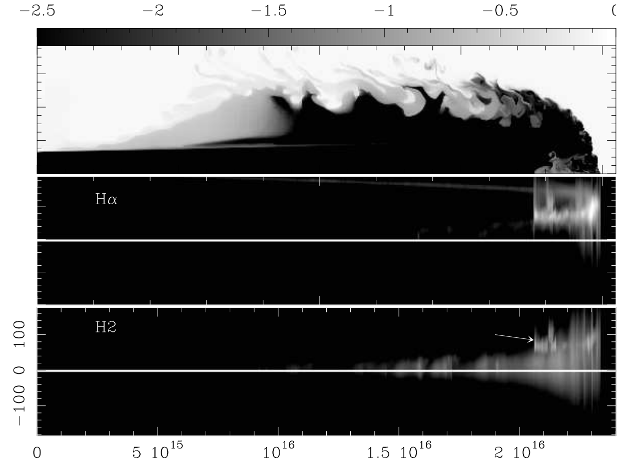

Fig. 3. The accelerating jet at 140 yrs. Top panel: H_2 fraction; center panel: Hα position-velocity diagram; bottom panel: H_2 position-velocity diagram.

jet) and the plug of molecular gas has a velocity of nearly $85\,\mathrm{km\,s^{-1}}$.

Figure 3 shows the fraction of the gas which is molecular (top panel); one can see that the molecular plug has a H_2 fraction of roughly 10% which is consistent with the fraction in the molecular layer which forms in the plane-parallel simulation above. The central and lower panels of this figure show position-velocity diagrams for the emission of the Hα line and the 1–0 line of H_2, respectively. The emission that corresponds to the molecular plug is indicated by the arrow in the lower panel. These features are distinct from the more diffuse emission from the bow-shock wings and are clearly shared by the atomic and molecular emission. Since shared features of atomic and molecular emission are found in observations, this is an indication that we could be on the right track.

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