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ULTRAVIOLET H_2 EMISSION FROM HH2

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RESUMEN

El espectro de HH2 tomado con el *Telescopio Ultravioleta Hopkins (HUT)*, muestra la banda de emisión Lyman debajo de 1200 Å y bandas de H_2 en el cuasi continuo a mayores longitudes de onda. Esto puede resultar, ya sea por flourescencia de Lyα (como en otros objetos HH), o por excitación colisional por electrones calientes. Bajo la hipótesis de flourescencia resulta difícil explicar la carencia de líneas fuertes e individuales, mientras que bajo la hipótesis de colisiones es necesario explicar la mezcla de electrones calientes dentro del gas molecular. El límite superior para el flujo de O VI parece estar en contradicción con las predicciones de modelos de choque de proa los cuales igualan el ancho de las líneas observadas de HH2A$'$ y HH2H.

ABSTRACT

The *Hopkins Ultraviolet Telescope* spectrum of HH 2 shows Lyman band emission below 1200 Å, and H_2 bands the quasi-continuum at longer wavelengths. It could arise either from Lyα fluorescence (as in other HH objects) or collisional excitation by hot electrons. It is difficult for the fluorescence hypothesis to explain the lack of individual strong features, while the collisional hypothesis must explain the mixing of hot electrons into molecular gas. The upper limit to the O VI flux appears to conflict badly with the predictions of bow shock models which match the observed line widths of HH2A$'$ and HH2H.

Key words: **ISM: JETS AND OUTFLOWS — SHOCK WAVES — ULTRAVIOLET: INTERSTELLAR**

1. INTRODUCTION

The faint emission line knots known as Herbig-Haro objects (Herbig 1951; Haro 1952) are shock waves driven by (and in) outflows from young stars (Schwartz 1977; Dopita 1978; Raymond 1979). Though the flows are sometimes too complicated to sort out, there are four basic emission structures. Knots in highly collimated jets are generally slow shock waves in cool, largely neutral atomic gas. Typical shock speeds are 20 km s^{-1}, and the shocks are generally attributed to variations in the speed or direction of the jet (Falle & Raga 1993; Hartigan, Morse, & Raymond 1994; Biro & Raga 1994). Models based on jet instabilities predict larger knot spacing than is observed (Falle 1994). Bright emission at the end of the jet arises when the jet material encounters the high pressure region of the working surface, creating a shock at the Mach disk, and also a bow shock driven into the interstellar medium. Finally, some HH jets have cleared out cavities in the parent clouds, and the walls of these cavities may be heated by slow shocks or turbulent dissipation (e.g., Cantó & Rodríguez 1980). In principle, any of these four structures might produce H_2 emission.

Complicated flow structures are created by Kelvin-Helmholtz, Rayleigh-Taylor and thermal instabilities (Blondin, Königl, & Fryxell 1989; de Gouveia Dal Pino & Benz 1993; Stone & Norman 1993), but simple bow shock models do a remarkably good job of predicting relative intensities and the line profiles of the optical and UV emission lines (Hartmann & Raymond 1984-HR; Raga & Böhm 1985-RB; Hartigan, Raymond, & Hartmann 1987-HRH; Morse et al. 1992). In particular, the relationship between line widths and excitation levels (e.g., [O III]/Hβ ratios) and the character of the line profile as a function of viewing angle work out quite well. Recent *HST* observations show that HH objects which are fairly simple at 1″ resolution are far more complex when seen at 0.1″ resolution (Schwartz et al. 1993; Heathcote et al. 1996). The dynamical complexity makes spectral diagnostics for the nature of the H_2 excitation and the physical processes in the exciting shock waves especially important. The relationship between the high velocity material seen at optical wavelengths and the slower, denser outflows seen in CO has been controversial for many years (e.g., Chernin & Masson 1995), and H_2 emission offers a direct look at the interaction.

Several physical processes have been suggested to account for the IR and UV emission of HH Objects, and several types of shock or turbulent mixing models have been considered as the ultimate energy sources. An excellent review is given by Brand (1995). Collisional excitation by neutrals or electrons, resonance fluorescence of Lyα, continuum fluorescence, and formation pumping may all contribute. The intensity ratios of the infrared lines generally imply excitation temperatures in the 2000–3000 K range, and the weakness of high excitation IR lines argues against a strong fluorescent or formation pumping contribution in the IR (but see Wright et al. 1997 for an exception). The UV emission in HH43 and HH47 shows the specific H_2 transitions produced by Lyα absorbed by the v = 2, J = 5 state of H_2, implying a dominant role for fluorescence, at least in the UV spectra of these objects.

The IR excitation is generally attributed to C-shocks (continuous flows which gradually heat the gas without dissociating it, converting nearly all the energy dissipated into H_2 infrared lines; Draine 1980), J-shocks (ordinary shocks showing a sharp jump in fluid parameters, generally dissociating H_2 and converting most of the energy dissipated into Lyα; see Draine & McKee 1993), or turbulent mixing of hot and cool gas (Raga, Cabrit, & Cantó 1995). UV fluorescence requires both strong Lyα emission and a large enough column density of H_2 in the excited state to absorb a substantial fraction of the Lyα photons. Possibilities include a J-shock and a C-shock close together, reformation of H_2 behind a J-shock, an MHD precursor ahead of a J-shock (Hartigan, Curiel, & Raymond 1989; Curiel et al.1995), or perhaps a turbulent mixing region which slowly heats the molecular gas and produces Lyα by recombination of the hot gas. This paper considers the implications of the UV spectrum of HH2 for the nature of the excitation.

The brightest Herbig-Haro objects in the sky, HH1 and HH2, provided some of the earliest spectral evidence that HH objects are shock waves (Schwartz 1977) and the first tests of bow shock models for their emission line intensities and profiles (HR; RB; HRH; Noriega-Crespo, Böhm,& Raga 1989). Their proper motions exceed 300 $km\,s^{-1}$ (Herbig & Jones 1981), and line widths of some knots reach 250 $km\,s^{-1}$ (HR). The correlation of line widths and the excitation of many of the knots (as judged by the [O III]/Hβ ratio) fits nicely into the bow shock picture, and the line profiles bear a respectable, though not perfect, resemblance to bow shock predictions (HR; RB; HRH). In these models, a bullet or jet drives a roughly paraboloidal shock wave into the ambient cloud. At the bow shock surface, gas encounters an oblique shock. The normal component of its velocity is the effective shock speed (determining the post-shock temperature) and the parallel component is conserved (contributing to the shape of the line profile). These models are especially successful with relatively simple bow shock structures such as HH30 (Morse et al. 1992).

However, HH2 has turned out to be far more complex than envisioned in the early bow shock models. The *HST* images of Schwartz et al. (1993) show high contrast structure down the the resolution limit, presumably due to the dynamical instabilities mentioned above. Very dense, cold ambient material seen in ammonia emission might also help fragment the flow (Torrelles et al. 1992). The UV spectrum of HH2 shows the anticipated C IV emission (Böhm et al. 1987; Raymond et al. 1988 - RHH), but not the N V. The blue continuum observed in the optical matches the prediction of hydrogen 2-photon emission from neutrals excited as they enter the shock (Dopita, Binnette, & Schwartz 1982), but the continued rise shortward of 1450 Å cannot be accounted for by 2-γ emission. Infrared H_2 lines show intensity ratios corresponding to 2500 K, as might be expected in a C-shock or a J-shock with an MHD precursor (Elias 1980), but the association of H_2 emission with very high excitation knots is surprising (Davis, Eisloffel, & Ray 1994; Curiel 1992).

We obtained a spectrum of HH2 with the *Hopkins Ultraviolet Telescope* to investigate its molecular emission and to search for the O VI emission line predicted by bow shock models.

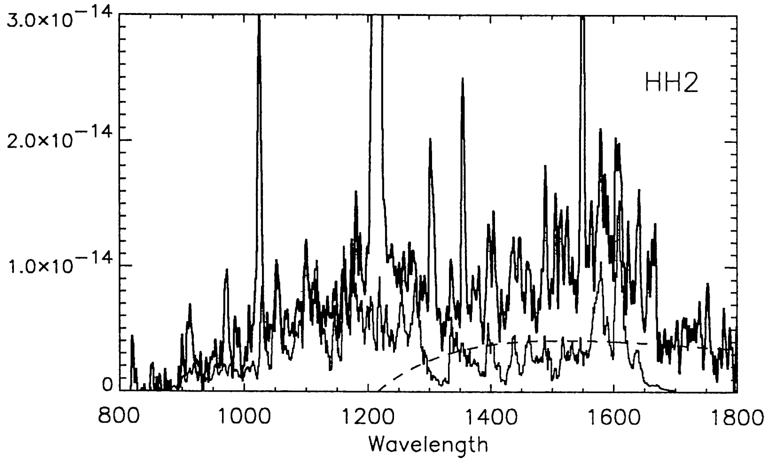

Fig. 1. *HUT* spectrum of HH2 (heavy line). The features at 920, 1025, 1215, 1300 and 1355 Å are terrestrial airglow. The features at 1550 and 1665 Å are C IV and O III] emission lines. The light line is the Liu & Dalgarno model for collisionally excited H_2 scaled to the features at 1050 and 1105 Å. The dashed line is the hydrogen 2-photon continuum scaled to the flux at 1700 Å.

2. OBSERVATIONS

The *Hopkins Ultraviolet Telescope* was flown as part of the Astro-2 space shuttle mission in March 1995. It obtained 2–4 Å resolution spectra over the wavelength range 850–1840 Å. Its 0.9 m primary mirror feeds a prime focus spectrograph with a photon-counting detector. The instrument is described in Davidsen et al. (1992) as it was flown on Astro-1. For the Astro-2 mission, the primary mirror and the grating were coated with higher efficiency SiC coatings which improved the throughput considerably (Kruk et al. 1995). The radiometric calibration is believed to be accurate to 5%.

HH2 was observed on 1995 March 13. The observation straddled the day-night terminator. To minimize contamination by airglow lines prominent in the sunlit portion of the orbit, we used the 12″ diameter aperture during the day, and then, to maximize the source counting rate, switched to the 20″ aperture during the night. The observations were centered on HH2H ($05^h39^m59^s7, -6°49'02''$ 1950). Totals of 1116 and 1098 seconds of good data were obtained during the day and night, respectively. The 12″ diameter aperture is sufficiently large that some photons are likely to have been detected from HH2D, but HH2A′ should have been excluded. With the 20″ aperture, most of HH2 was sampled, with the exception of the low excitation knots HH2E, HH2K, and HH2L. Böhm et al. (1987) found that the C IV emission line region of HH2H was unresolved at the 5″ resolution of *IUE*, while the continuum emission was somewhat more extended. Figure 1 shows the spectrum from the night-time portion of the orbit, along with a model described below.

The *HUT* spectrum shows geocoronal Lyman lines and lines of O I. There is a broad hump centered near 1500 Å and a fainter, fairly flat continuum longward of 1680 Å. The spectrum confirms the argument of Böhm et al. (1987) that the faint continuum seen by *IUE* is real, along with their interpretation as H_2 emission. The features at 1053 and 1101 Å in the *HUT* spectrum are clearly the H_2 blends expected at these wavelengths. However, Böhm et al. took 1500 Å hump to be continuum radiation produced during dissociation, while the *HUT* spectrum shows a blend of many H_2 lines. The broad hump near 1500 Å appears somewhat brighter in the *HUT* spectrum, but the shape is very similar to that seen with *IUE*. We do not detect any of the H_2 Lyman emission features pumped by Lyβ that are seen in the spectrum of Jupiter (Feldman et al. 1993). The reason is probably the efficient conversion of Lyβ to Hα plus a 2-γ pair when Lyβ photons are absorbed by H atoms. The 2-γ continuum, mostly due to direct excitation of neutrals passing though the shock (Dopita et al. 1982), accounts for the continuum at longer wavelengths, as the H_2 emission does not extend beyond about 1640 Å. The 1671–1740 Å band represents 4.8% of the 2-γ flux, implying a total 2-γ emission about 65% larger than the value derived from *IUE* by RHH.

3. DISCUSSION

3.1. Lack of O VI Emission

As described above, we did not detect the O VI doublet, and the upper limit is about 20% of the C IV flux. According to theoretical models of bow shocks, the Full Width at Zero Intensity of the emission lines equals the bow shock velocity, and for HH2A′ and HH2H that implies $v_{bs} \simeq 190 - 250\,\mathrm{km\,s^{-1}}$ (HRH). The bow shock models then predict I(O VI) / I(C IV) to be at least 2. Even with allowance for uncertain reddening the lack of O VI emission contradicts the models. It is conceivable that molecular hydrogen attenuates the O VI lines. Jenkins & Peimbert (1997) list H_2 lines at $\lambda\lambda$ 1037.149, 1031.192. These are unlikely to seriously affect the O VI lines 0.5 and 0.7 Å away. However, the IR emission lines of H_2 imply substantial populations in vibrationally excited levels which are not usually observed in absorption. While this possibility should be investigated further, it is unlikely that H_2 could so completely wipe out the very broad O VI doublet lines.

While the complex small scale structure discovered in *HST* images of HH2 (Schwartz et al. 1993) at first glance offers a reason to discount the bow shock models, it does not change the overall energetics or the fact that for reasonable oblique shock geometries the line width should still equal the maximum shock velocity. This is a purely geometrical argument, in that the maximum line-of-sight velocity generated by an oblique shock moving in the plane of the sky (as is the case for HH1 and HH2) is $\max(v_{bs}\sin\theta\cos\theta) = v_{bs}/2$. The most likely explanation for the discrepancy is a serious departure from the plane parallel, steady flow shocks models used to construct the bow shock models. Possibilities include turbulent mixing of hot and cool gas by shear-generated turbulence (e.g., Slavin, Shull, & Begelman 1993), a large neutral (or molecular) fraction at the shock front (RHH), or a flow time smaller than the radiative cooling time.

3.2. Molecular Hydrogen Emission

The detection of H_2 bands below 1200 Å, as well as the noisy but significant band structure seen at longer wavelengths (e.g., 1610, 1510, and 1580 Å) shows that the UV continuum detected by *IUE* below 1600 Å is H_2 emission. At longer wavelengths, the continuum is consistent with hydrogen two-photon emission produced largely by collisional excitation to the 2s level, as expected for shocks encountering largely neutral gas (Dopita et al. 1982; Cox & Raymond 1985). The identification of H_2 emission resolves the question of the "blue continuum" investigated by Böhm et al. (1987). It was identified as H_2 dissociation continuum by Böhm et al. (1987) because it lacks the dominant Lyman emission features reported by Schwartz (1983) in HH43 and HH47. Those objects showed strong emission in a set of transitions pumped by Lyα (1258, 1272, 1431, 1446, 1505, 1547 and 1562 Å), as has been seen in spectra of Burnham's Nebula (Brown et al. 1981). Several of these features can be seen in Figure 1, but they were not apparent in the *IUE* spectra. Curiel et al. (1995) observed a small part of the UV spectrum of HH47 at higher resolution with GHRS. They confirmed the expected Lyα fluorescence transitions at 1270.98, 1271.83 and 1293.75 Å, but found an unexpected feature at 1293.35 Å as well.

The *HUT* spectrum of HH2 shows that molecular hydrogen produces most of the UV emission below 1620 Å. Dissociation continuum undoubtably contributes, but a substantial fraction of the molecular emission originates in bound-bound transitions. The mystery is why the spectrum looks so different from the HH43 and HH47 spectra. One possibility is that Lyα fluorescence produces the H_2 emission in HH2 as well as in the other objects, but that the Lyα photons pump a much larger set of levels in H_2. Another possibility is that the H_2 emission is produced by collisional excitation. We consider these excitation mechanisms in turn.

3.2.1. Lyα Fluorescence

The fluorescent spectrum seen in HH43 is created by the pumping transition, B-X (1-2) P(5), at 0.4 Å from Lyα line center (Schwartz 1983). There are many other possible pumping transitions (Black & van Dishoeck 1987). It seems plausible that the 100 $\mathrm{km\,s^{-1}}$ width in HH47 (Hartigan, Raymond, & Meaburn 1990) makes it possible to pump one or two more transitions than in HH43, each giving rise to a set of emission lines. HH2, with a 200 $km\,s^{-1}$ line width, could distribute the converted Lyα photons among a still larger number of lines. This is energetically plausible. Based on shock wave models (HRH) we can infer the Lyα luminosity from the Hα luminosity. Taking a distance of 500 pc (which actually scales out of the comparison with molecular luminosity), $L_{H\alpha} = 2.6 - 5 \times 10^{31}$ erg s^{-1} for the knots within the 20″ aperture. Scaling the 200 $km\,s^{-1}$ bow shock model of HRH to the Hα luminosity (the ratio is insensitive to model parameters), $L_{Ly\alpha} = 5 - 10 \times 10^{32}$ erg s^{-1}. This is consistent with the 2-γ/Lyα ratios of the HRH models and the 2-γ flux, provided that the reddening is low. The luminosity of the H_2 emission is $2 - 10 \times 10^{32}$ ergs s^{-1}, depending on the reddening correction, so at least 20% of the Lyα photons must be fluoresced to match the observed brightness. Thus Lyα fluorescence is energetically possible.

The second test of the hypothesis of fluorescent pumping by a large number of transitions is the optical depth of the transitions to be pumped. Since a large fraction of the Lyα luminosity must be converted, the optical depths of the pumping transitions must be of order one. We can determine the optical depths by consideration of the infrared emission. Based on a flux of 15×10^{-14} erg cm^{-2} s^{-1} from a 10″ diameter aperture centered on HH2H (Elias 1980) in the (1-0)S(1) line and the images of Davis et al. (1994), we estimate a column density of the upper state to be $N(v, J = 1, 1) = 10^{16}$ cm^{-2}. The lower level of the B-X(1-2)P(5) transition lies 0.6 eV higher, so even with a Boltzmann distribution of populations at typical temperature T = 2500 K (e.g., Brand 1995), its column density is less than 10^{15} cm^{-2}. For an absorption oscillator strength of 0.029 (Black & van Dishoeck 1987), and a line width of 30 $km\,s^{-1}$, this gives an optical depth of 3.0. A smaller line width would imply a larger optical depth, but the line would intercept a correspondingly smaller fraction of the Lyα photons. Most of the potential pumping transitions arise from higher-lying vibrational levels. Each vibrational level is about 0.5 eV above the last, so that the populations drop by an order of magnitude for each vibrational level. Thus transitions arising from vibrational levels 4 and above should be optically thin. This leaves only three potential pumping transitions in the Black & van Dishoeck list, and they would probably not produce a broad enough distribution of fluorescent lines.

3.2.2. Collisional Excitation

Böhm et al. (1987) also remarked that collisional excitation of H_2 by electrons might account for the UV emission of HH2H. Liu & Dalgarno (1996) have computed theoretical H_2 emission spectra for a variety of H_2 temperatures and electron energies. The prediction for 1000 K H_2 and 20 eV electrons resembles the H_2 contribution to HH2H quite closely. Figure 1 shows the *HUT* spectrum with the Liu & Dalgarno model scaled to match the emission below 1200 Å and the spectral shape of hydrogen 2-γ emission matched to the long wavelength continuum. Both the observations and the model show discrete features at 1053 and 1101 Å and a blend of weak features at longer wavelengths out to the observed cutoff near 1640 Å, with a broad minimum between 1300 and 1450 Å. Most of the Liu & Dalgarno spectra have a dominant strong emission feature near 1610 Å, but the combination of low electron energy and relatively high excitation of the molecules provides for excitation of a large number of states and divides the emission among a very large number of lines.

While the agreement is impressive, one should be cautious about this interpretation. From the observational point of view, reddening will reduce the short wavelength emission compared with the longer wavelength range, and H_2 absorption both local to HH2 and along the line of sight will cut into some of the emission features, especially those at 1053 and 1101 Å. On the theoretical side, it is difficult to mix hydrogen molecules with hot electrons before dissociating the molecules. A shock wave might do it in principle, but hot ions dissociate H_2 very rapidly. The second problem is the molecular luminosity. Based on the estimate above, the observed portion of HH2 produces over 10^{43} H_2 photons per second. For a pre-shock density of 500 molecules cm^{-3}, a shock velocity of 200 $km\,s^{-1}$, and a shock area of 10^{33} cm^2, this requires 1–5 photons per molecule. While excitation of the Lyman bands can produce 10 photons per molecule (thanks to the small branching ratio to the vibrational continuum), excitations to the triplet states destroy molecules quite effectively. Even without collisions with protons or neutral atoms, it is unlikely that a molecule can produce more than 3 UV photons before it is destroyed. Thus it is necessary to mix hot electrons into molecular gas which is hot enough to excite the vibrational levels ($\simeq$ 1000 K) but not hot enough to rapidly dissociate the molecules ($\simeq$ 10000 K). Neither a standard J-shock nor a standard C-shock (see Draine & McKee 1993) is well-suited to this task. A J-shock with an MHD precursor (Hartigan et al. 1989) might have the right properties, but sufficiently detailed models are not available, and it is difficult to see how an MHD precursor could exist at such high speeds and ionizing photon fluxes. Turbulent mixing is not an obviously better candidate.

A potential side effect of collisional excitation of the H_2 UV emission is the reduction of the energy available to heat the gas to O VI-producing temperatures. If the bow shock tip encounters largely molecular gas, the effective shock velocity may drop enough to drastically reduce the O VI emission. However, it is difficult to see how molecules can survive the ionizing radiation field near the bow shock tip.

4. CONCLUSIONS

The UV spectrum of HH2 shows several of the expected UV emission lines, but the O VI emission predicted by 200 $\mathrm{km\,s^{-1}}$ bow shock models is absent. This conflicts not just with the details of the bow shock models, but with the more general idea that a 200 $\mathrm{km\,s^{-1}}$ wide line profile requires 200 $\mathrm{km\,s^{-1}}$ radiative shock waves.

The *HUT* spectrum also shows discrete Lyman band emission below 1200 Å. It shows some band structure at longer wavelengths as well, pinning down the nature of the continuum seen with *IUE*. Both Lyα fluorescence and collisional excitation of H_2 may have attractive features for explaining the UV emission, but both have drawbacks as well. It is very hard to see how any MHD shock (a C-shock or a J-shock with a precursor) can exist so close to the ionizing flux of HH2H. Either type of MHD structure requires both a strong magnetic field and a very low ionization fraction to make the supersonic flow sub-Alfvénic. It is equally difficult to see how a J-shock or turbulent mixing can produce H_2 UV photons efficiently enough to account for the observations.

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