THE ASTROPHYSICAL JOURNAL, 223: L41–43, 1978 July 1


# MOLECULAR HYDROGEN EMISSION FROM T TAURI STARS

S. BECKWITH, I. GATLEY, AND K. MATTHEWS
California Institute of Technology
AND
G. NEUGEBAUER
Hale Observatories, California Institute of Technology, Carnegie Institution of Washington
*Received 1978 March 13; accepted 1978 April 13*

## ABSTRACT

Emission in the $v = 1 \rightarrow 0\ S(1)$ line of molecular hydrogen has been detected in T Tauri; it has been searched for and is not seen in four other T Tauri stars. The emitting region is $\sim 5''$ in size and is probably centered on the star. For T Tau a measurement of the atomic hydrogen B$\gamma$ line strength and an upper limit on the strength of the $v = 2 \rightarrow 1\ S(1)$ line of $H_2$ are also given.

*Subject headings:* infrared: spectra — molecular processes — stars: mass loss

### I. INTRODUCTION

Molecular hydrogen emission has recently been detected from the Orion Nebula (Gautier *et al.* 1976), from planetary nebulae (Treffers *et al.* 1976; Beckwith, Persson, and Gatley 1978), and from the galaxy NGC 1068 (Thompson, Lebofsky, and Rieke 1978). Because this emission is not understood it may be useful to extend the range of observations to classes of objects other than those listed above. In this regard T Tauri stars are good candidates; they are often found in the vicinity of molecular clouds, and are emission-line objects (see, e.g., Strom, Strom, and Grasdalen 1975).

We have searched for molecular hydrogen emission in the $v = 1 \rightarrow 0\ S(1)$ line at 2.12 $\mu$m in five T Tauri stars. In this *Letter* the observational results of this limited search are presented. The detection of $H_2$ emission in one of these objects satisfies our aim of finding a new class of molecular hydrogen sources; however, the present observations do not bear directly on the problem of the excitation mechanism.

### II. OBSERVATIONS

The observations were made with the 2.5 m Hooker telescope at Mount Wilson and the 5 m Hale telescope at Palomar Mountain during 1977 October and November. An Ebert-Fastie grating spectrometer with 17 Å resolution was used throughout; the instrument and procedures for its use are described by Beckwith *et al.* (1978). For the present observations the focal plane diaphragm was generally $5''$ in diameter and the beam spacing was $30''$; in the case of T Tau, measurements were also made with a $10''$ diaphragm and a $60''$ beam spacing for sky subtraction. No air-mass corrections have been applied to the data.

Flux calibration was achieved by observations of $\beta$ Per. The 2.1 $\mu$m flux density of this star is assumed to be 83 Jy, while the continuum is assumed to follow the Rayleigh-Jeans law in the 2 $\mu$m atmospheric window.

For each line seven wavelengths were observed; the wavelength of the $v = 1 \rightarrow 0\ S(1)$ line of $H_2$ measured in air (2.1213 $\mu$m), and wavelengths on each side of the line displaced 0.5, 1, and 2 times the spectrometer resolution element of 17 Å. In the case of T Tau positions centered $5''$ north, south, east, and west were also measured with a $5''$ focal plane diaphragm; at these positions only the wavelength of the $v = 1 \rightarrow S(1)$ line and a representative continuum wavelength of 2.1255 $\mu$m were measured. For T Tau the $v = 2 \rightarrow 1S(1)$ line of $H_2$ and the B$\gamma$ line of atomic hydrogen were also measured; as for the $H_2$ line, seven wavelengths on and adjoining each line were observed.

### III. RESULTS

Figure 1 shows the measured spectra in the vicinity of the $v = 1 \rightarrow 0\ S(1)$ line of $H_2$ for five T Tauri stars. Figure 1 also shows measurements of T Tau made with both a $5''$ and a $10''$ focal plane diaphragm. The line strength in the former is $(3.1 \pm 0.4) \times 10^{-13}$ ergs s$^{-2}$ cm$^{-2}$, while that in the latter is $(5.7 \pm 1.0) \times 10^{-13}$ ergs s$^{-1}$ cm$^{-2}$. The increase in line strength with increasing diaphragm size indicates that the emitting region is probably larger than $5''$; this result is only marginally significant ($2.5\ \sigma$). Table 1 lists the measured line strengths at positions $5''$ north, south, east, and west of T Tau; although the $H_2$ line was not positively detected at any of these positions, the upper limits on the line strengths are consistent with the increase seen between the $5''$ and $10''$ diaphragms. The emission is therefore probably centered on the star. No emission was detected in the other four stars shown; the line strengths are $< 1.3 \times 10^{-13}$ ergs s$^{-1}$ cm$^{-2}$ ($3\ \sigma$).

The $v = 2 \rightarrow 1\ S(1)$ line of $H_2$ was also searched for at wavelengths around 2.25 $\mu$m. No identifiable feature was observed in a $5''$ diaphragm; the $3\ \sigma$ upper limit on the line strength is $3 \times 10^{-13}$ ergs s$^{-1}$ cm$^{-2}$.

Figure 2 shows the spectrum of T Tau in the vicinity of the B$\gamma$ line of atomic hydrogen. The line is seen with a strength of $8 \times 10^{-13}$ ergs s$^{-1}$ cm$^{-2}$.

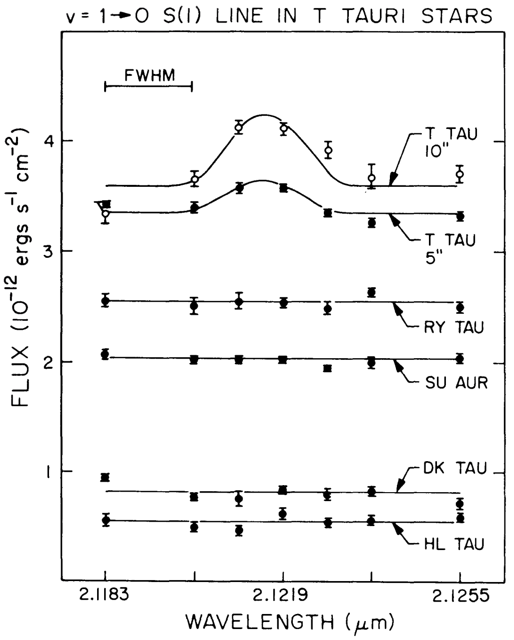


FIG. 1.—The spectra of five T Tauri stars at the position of the $v = 1 \rightarrow 0\,S(1)$ line of molecular hydrogen. In each case the two longest and two shortest wavelengths are used to define the continuum level indicated. For the spectrum of T Tau the measured instrumental profile, arbitrarily normalized, has been roughly fitted to the data. Except for the "T Tau 10″ spectrum," the observations were made with a 5″ focal plane diaphragm.

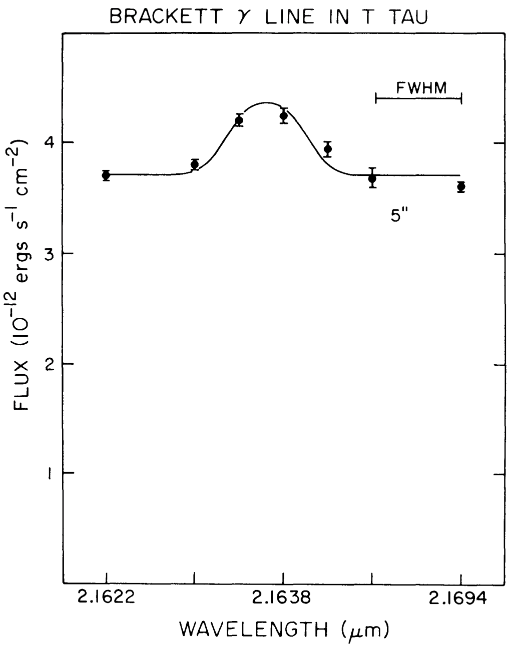


FIG. 2.—The spectrum of T Tau at the position of the B$\gamma$ line of atomic hydrogen as measured with a 5″ focal plane diaphragm. The continuum level indicated was defined by the two longest and two shortest wavelengths measured. The measured instrumental profile, arbitrarily normalized, has been roughly fitted to the data.

TABLE 1

FLUX MEASUREMENTS OF THE $v = 1 \rightarrow 0\,S(1)$ LINE NEAR T TAURI

| Position | Line Flux ($10^{-13}$ ergs s$^{-1}$ cm$^{-2}$) |
|---|---|
| 5″ north.............. | $+0.6 \pm 0.6$ |
| 5″ east............... | $+0.4 \pm 0.4$ |
| 5″ south.............. | $-0.1 \pm 0.6$ |
| 5″ west............... | $+0.6 \pm 0.6$ |

## IV. DISCUSSION

The major results of this *Letter* are that molecular hydrogen emission is seen from T Tauri and that the region of emission is probably extended (>5″). The strength of molecular hydrogen emission in T Tauri is at least 3 times greater than the strength of this emission in any of the other T Tauri stars in the sample.

The excitation mechanism for the $H_2$ in T Tau cannot be determined from the present data. As in previously known cases of $H_2$ emission, we are confronted with a physical system in which several plausible alternatives for the excitation mechanism exist. From observations of atomic hydrogen lines, such as the present B$\gamma$ line measurement, it is known that some mechanism in the outer envelope of the T Tauri stars is capable of ionizing hydrogen. Therefore the $H_2$ molecules could possibly be excited by ultraviolet radiation or by electron collision in the interface between the ionized and neutral material. On the other hand, a high mass-loss rate from T Tau may cause supersonic shocks in the surrounding neutral material (Schwartz 1975). It is possible that these shocks excite the $H_2$ in the manner proposed to explain the molecular hydrogen emission from the Orion Nebula (Hollenbach and Shull 1977; Kwan 1977).

For the case of shock excitation it is possible to estimate from the observations the mass-loss rate and neutral particle density in the shocked region. If the $H_2$ emission is assumed to come from an optically thin, uniform spherical surface 5″ in diameter, then the surface brightness of the $v = 1 \rightarrow 0\,S(1)$ line is $\sim 3 \times 10^{-4}$ ergs s$^{-1}$ cm$^{-2}$ sr$^{-1}$. If we assume a 15 km s$^{-1}$ shock velocity, Kwan's model for shock excitation, and this value for the surface brightness of the $v = 1 \rightarrow 0\,S(1)$ line, then we find the density of molecular hydrogen in the preshocked region to be $\sim 2 \times 10^4$ cm$^{-3}$. With this density and shock velocity, the pressure necessary to push the shock continuously can be derived; the result is $\sim 10^{-7}$ dynes cm$^{-2}$. If this pressure is equated to the momentum per second associated with mass loss from the star and the velocity of the material is 200 km s$^{-1}$, then a mass-loss rate of $5 \times 10^{-8}\,M_\odot$ yr$^{-1}$ is required to sustain the shock. This result is of the same order of magnitude as mass-loss rates derived by other means (Kuhi 1964; Schwartz 1975).

Differences between T Tau and the other stars in this sample may include the density of the neutral material surrounding the stars, the mass-loss rate, or the ultraviolet luminosity of the emission-line regions. Inasmuch as the mass-loss rates for the two brightest stars in the sample, T Tau and RY Tau, are about the same (Kuhi 1964), and the Balmer lines are actually the strongest in HL Tau (Rydgren, Strom, and Strom 1976), we suggest that the density of surrounding material is the most critical factor for molecular hydrogen emission. In support of this suggestion are the observations of CO emission, which is relatively bright in the case of T Tau (Knapp *et al.* 1977), the presence of emission nebulosity associated with T Tau (Burnham 1890, 1894; Schwartz 1974), and the relative brightness of T Tau at far-infrared wavelengths (Harvey, Thronson, and Gatley 1979).

Unfortunately, cloud densities, mass-loss rates, and ultraviolet luminosities are not well known for the stars in our sample. It is therefore not possible to come to any definite conclusions about the brightness of $H_2$ emission in T Tau relative to other T Tauri stars. Despite the difficulties in interpreting the data we have presented, it is likely that further spectroscopic studies of T Tauri stars will be a fruitful source of information about molecular hydrogen emission and the star-formation process.

On 1978 March 2 Gene Hancock died after many years as Night Assistant at Mount Wilson. We are grateful to Gene both for his contribution to this paper and for his contributions to Mount Wilson. We also thank R. Cadman and G. Tuton for their assistance with the observations. We thank S. Eric Persson for his support of this project through discussions and help with the observations, and Paul Harvey for giving us his infrared data in advance of publication. This research was supported by National Aeronautics and Space Administration grant NGL 05-002-207 and National Science Foundation grant AST 74-18555A2.

## REFERENCES

Beckwith, S., Persson, S. E., and Gatley, I. 1978, *Ap. J.* (*Letters*), **219**, L33.
Beckwith, S., Persson, S. E., Neugebauer, G., and Becklin, E. E. 1978, *Ap. J.*, **223**, in press.
Burnham, S. W. 1890, *M.N.R.A.S.*, **51**, 94.
———. 1894, *Pub. Lick Obs.*, **2**, 175.
Gautier, T. N., III, Fink, U., Treffers, R. P., and Larson, H. P. 1976, *Ap. J.* (*Letters*), **207**, L129.
Harvey, P. M., Thronson, H. A., and Gatley, I. 1979, in preparation.
Hollenbach, D. J., and Shull, J. M. 1977, *Ap. J.*, **216**, 419.
Knapp, G. R., Kuiper, T. B. H., Knapp, S. L., and Brown, R. L. 1977, *Ap. J.*, **214**, 78.
Kuhi, L. V. 1964, *Ap. J.*, **140**, 1409.
Kwan, J. 1977, *Ap. J.*, **216**, 713.
Rydgren, A. E., Strom, S. E., and Strom, K. M. 1976, *Ap. J. Suppl.*, **30**, 307.
Schwartz, R. D. 1974, *Ap. J.*, **191**, 419.
———. 1975, *Ap. J.*, **195**, 631.
Strom, S. E., Strom, K. M., and Grasdalen, G. 1975, *Ann. Rev. Astr. Ap.*, **13**, 187.
Thompson, R. I., Lebofsky, M. J., and Rieke, G. H. 1978, preprint.
Treffers, R. R., Fink, U., Larson, H. P., and Gautier, T. N., III. 1976, *Ap. J.*, **209**, 793.

S. Beckwith, I. Gatley, K. Matthews, and G. Neugebauer: Downs Laboratory of Physics 320–47, California Institute of Technology, Pasadena, CA 91125