Letter to the Editor

The spatial distribution of excited H$_2$ in T Tau:
a molecular outflow in a young binary system

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Abstract. Strong extended emission from molecular hydrogen in the $v = 1 \rightarrow 0$ S(1) transition is mapped around T Tau. In addition, the $v = 2 \rightarrow 1$ S(1) line is detected close to the star. The ratio of the two transitions is consistent with an excitation process in which both fluorescence by stellar ultraviolet radiation and collisions in a warm, dense medium play a role. The morphology is interpreted as emission from a molecular outflow which appears to wiggle as a result of the fact that T Tau is a binary system seen almost pole–on. It is shown that an outflow with a small opening angle can reproduce the observed extended emission. From comparison with previous studies it is argued that the molecular outflow originates from T Tau S, the infrared component. The presented model constrains the orientation and geometry of the system.

Key words: Stars: T Tauri – Stars: pre–main–sequence – Stars: Formation – Stars: binaries – ISM: jets and outflows – ISM: molecules

1. Introduction

It is well established that the earliest stages of star formation are accompanied by a strong bipolar outflow well before the bulk of the mass in the system has been dissipated (Shu et al. 1987). The temporal history of these outflows (collimation, mass loss rates, orientation, etc.) is a matter of considerable interest since they blow away the surrounding molecular cloud and may influence the inner part of the circumstellar disk. Thus, processes associated with outflows drive young stellar objects toward their so-called T Tauri phase in which visible and ultraviolet radiation can emerge through "holes" in the molecular cloud created by the mass loss.

At a distance of 140 pc (Elias 1978), T Tau is one of the few T Tauri stars to have been studied from radio to X-ray wavelengths. Among its most unusual characteristics are an extended Herbig–Haro–like region called Burnham's nebula, the

presence of extensive infrared *and* ultraviolet fluorescence from molecular hydrogen, and non-thermal radio emission (Schwartz 1984). T Tau is accompanied by a close binary companion (T Tau S) which is only visible at infrared and longer wavelengths (Ghez et al. 1991). Despite the rather small visual extinction toward T Tau, it is clear from a number of molecular tracers that considerable amounts of circumstellar matter still surround the young stars (Weintraub et al. 1989), possibly accreting onto a circumstellar disk (Van Langevelde et al. 1994a).

Recent observations of H$_2$ emission at 2.12 μm in different Young Stellar Objects (YSO's) have shown it to trace the interactions of young stellar winds and outflows with their surrounding molecular clouds (Bally et al. 1993a,b; Davis et al. 1994). In T Tau the $v = 1 \rightarrow 0$ S(1) line is known to be strong and extended (Beckwith et al. 1978). Here we present high spatial resolution observations of the $v = 1 \rightarrow 0$ and $v = 2 \rightarrow 1$ S(1) emission lines from molecular hydrogen in the T Tau binary system. These emission lines result primarily from warm molecular material with $n_{H_2} > 10^4$ cm^{-3} and can therefore provide complementary information to optical forbidden line shock tracers such as the 6716/6731 Å [S II] doublet and other outflow tracers such as high-velocity CO and SiO. By comparing the new H$_2$ images with existing T Tau data we construct a detailed model of the geometry of this unusual binary system.

2. Observations

Observations of H$_2$ near–infrared emission toward T Tau were carried out on the nights of October 1 and 5, 1993, with the 4.2m William Herschel Telescope at La Palma, Canary Islands[1], using the MPE near–infrared camera FAST (Krabbe et al 1994). FAST uses a 62 × 58 InSb array with 0″.5 pixels; dispersion was

provided with a scanning Fabry-Perot (R=1050) in series with an R=50 circular variable filter which served as order sorter. On both nights the conditions were good, with a typical seeing of $0''.8$ at K band.

Repeated exposures of 100–200 seconds were made with the Fabry–Perot tuned to the $v = 1 \rightarrow 0$ S(1) line at 2.121 μm and $v = 2 \rightarrow 1$ S(1) line at 2.247 μm on both nights. Equal amounts of observing time were spent at off-line wavelengths on both sides of the lines before and after the on-line exposures. Flat-fielding, dark-current subtraction and removal of hot and cold pixels were performed using standard methods. Flux calibration was done using the standard star HR1552 (K=4.14, spectral type B2III).

The bright continuum of T Tau (K=5.4) saturates the detector array in the long exposures. These effects are taken out of the displayed images by blocking out an aperture of the size of the saturated region. The resulting image for the $v = 1 \rightarrow 0$ S(1) line is shown in Fig. 1. To overcome the limitations close to the stellar position, and to be able to measure most of the line flux originating close to the star, we made additional short integrations of 5 seconds each. This allows detection of $v = 1 \rightarrow 0$ S(1) at the stellar position at a level somewhat higher than the immediate surroundings.

3. Interpretation

From the short integration time images we estimate the total line flux to be (2.3 ± 0.2) 10^{-13} erg s^{-1} cm^{-2} in a $5''$ aperture. In a $10''$ aperture this value increases to (4.0 ± 0.3) 10^{-13} erg s^{-1} cm^{-2}. Both values are $\approx 25\%$ smaller than previous measurements by Beckwith et al. (1978). Taking all the contributions in the deeper images into account, the total detected $v = 1 \rightarrow 0$ S(1) flux is estimated at (9.6 ± 0.8) 10^{-13} erg s^{-1} cm^{-2}. The peak intensity in this map (excluding the T Tau position) is 3.6 $\times 10^{-4}$ erg s^{-1} cm^{-2} sr^{-1} about $3''$ north of T Tau.

The total flux in the $v = 2 \rightarrow 1$ S(1) line is more difficult to determine due to the strong continuum. Because this line is an order of magnitude weaker it is not practical to try to detect it in short exposures. Because of the very good seeing, however, a low–level counterpart to the emission $3''$ north of the stellar position is unambiguously detected. The $v = 2 \rightarrow 1$ S(1) brightness in this region is a factor of 10.5 ± 0.7 lower than the $v = 1 \rightarrow 0$ S(1) contribution. At the $20''$ S position, the $v = 1 \rightarrow 0$ S(1)/$v = 2 \rightarrow 1$ S(1) ratio is greater than 6.

3.1. Excitation

The excitation of H_2 toward T Tau over a region of 5–15$''$ has been modeled in detail by Black & Van Dishoeck (1987). T Tau provides an interesting case in which both collisional excitation and radiative pumping occur. Ultraviolet fluorescent emission of H_2 has been detected by Brown et al. (1981) and shows the characteristic signature of H_2 excited by intense stellar H Lyman α radiation out of the $v=2$, $J=5$ level. On the other hand, the high population in $v=2$ implied by the ultraviolet fluorescence can only be maintained by collisions in a dense

$(n > 10^5$ cm$^{-3})$ gas at $T \approx 2000$ K. The observed $v = 1 \rightarrow 0$ S(1)/$v = 2 \rightarrow 1$ S(1) ratio of about 10 close to the star is consistent with the interpretation by Black & Van Dishoeck (1987). Although such a ratio could also be produced in a warm, dense "photon–dominated" region around T Tau at lower temperature (Sternberg & Dalgarno 1989), the known ultraviolet flux of T Tau and the absolute intensity of the $v = 1 \rightarrow 0$ S(1) line are inconsistent with this model. Sensitive images of the H_2 flux distribution in higher excitation infrared lines, such as the $v = 3 \rightarrow 2$ S(1) and $2 \rightarrow 1$ S(3) and S(4) lines, or in the ultraviolet fluorescent lines, are needed to spatially distinguish the collisional and fluorescent excitation contributions.

The observed $v = 1 \rightarrow 0$ S(1) flux of 2.3 10^{-13} erg s^{-1} cm^{-2} in a $5''$ aperture can be produced by an H_2 column density of only 1.6×10^{18} cm^{-2} at T=2000 K. For comparison, the estimated total H_2 column density in this region is $\approx 3 \times 10^{22}$ cm^{-2} (Van Langevelde et al. 1994b), so that the observed H_2 comprises only a small fraction. If the high temperature is due to shocks, the observed intensity could be produced in a C–type shock with $V_s \approx 30$ km s^{-1} (Draine et al. 1983). Such shocks most likely originate from the interaction of a fast stellar jet with the surrounding medium, where the H_2 emission delineates the region where molecular gas is entrained in the flow and accelerated (Bally et al. 1992b).

3.2. Morphology

The $v = 1 \rightarrow 0$ S(1) transition (Fig. 1) shows an extended morphology, with the highest intensities arising close to T Tau. On scales of $2''$ the elongated structure can be interpreted as an outflow with a position angle of $\approx -25°$. A similar position angle can be seen in molecular gas in the wings of ^{12}CO emission by Weintraub et al. (1989), and in ionized material (Böhm & Solf 1994). In addition, there is extended emission on larger scales, which peaks about $20''$ south of T Tau. This H_2 emission appears to "coat" the outer edge of Burnham's nebula seen in ionized material (Schwartz 1975, and references therein). Taking into account the fact that T Tau is a binary (Dyck et al. 1982) and the very small inclination of the system, we show below by means of a ballistic model that the extended emission is also consistent with a molecular outflow.

In a binary system any outflow from one of the components will undergo prominent wiggles when the outflow velocity is comparable to the orbital velocity, since the orbital motion of the star is added to the outflow velocity. The resulting structure appears enhanced when the outflow axis is close to the line of sight and is determined by the orientation and orbital parameters of the system as well as the velocity and opening angle of the outflow.

First, it is assumed that the stellar orbits in the binary are perfectly circular and that the motion around the centre of mass is governed by the stellar components only. In addition the outflow axis is taken to be perpendicular to the orbital plane of the system, which is also assumed to be the plane of the disk. It is known that the optically visible star, T Tau N, is observed almost pole–on, and an inclination $|i| = 13°$ is adopted for
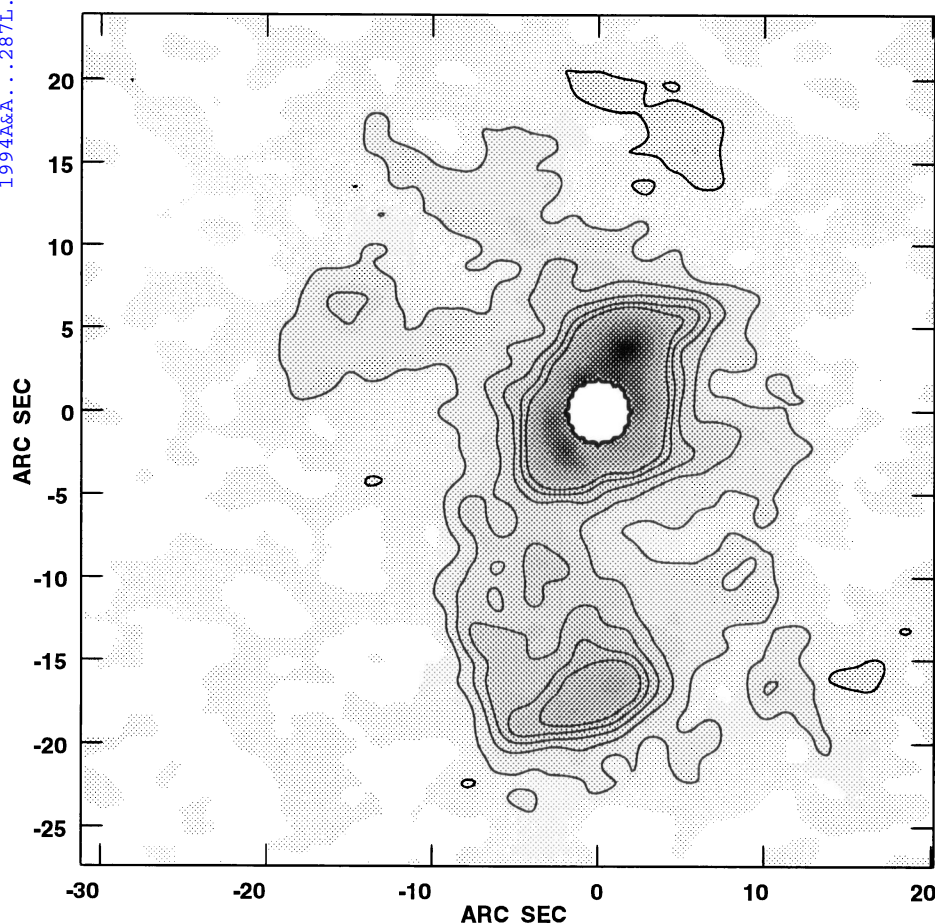
Fig. 1. The distribution of the $v = 1 \rightarrow 0$ S(1) line toward T Tau. The area where the strong continuum saturates the detector array is blanked. Contour levels are 1, 2, 3, 4, 5 × 1.75 10^{-5} erg s^{-1} cm^{-2} sr^{-1}. Grey levels are linear between 0 and 4 10^{-4} erg s^{-1} cm^{-2} sr^{-1}. The (0,0) refers to the position of T Tau.

the system (Herbst et al. 1986). Furthermore, the measured separation between T Tau N and T Tau S is 0''.65, with T Tau S lying to the south at position angle $\approx 175°$ (Ghez et al. 1991). Stellar masses of respectively 2 and 1 $M_\odot$ for these objects are used in the calculations (Bertout 1983; Beckwith et al. 1990). The position angle of the circumstellar disk on the sky is less certain, but both Van Langevelde et al. (1994b) and Weintraub et al. (1989) argue that the east side is moving toward the observer and the west side receding. We adopt a position angle of 70° for the line of nodes. As far as the system geometry is concerned there are only two uncertainties left: the sign of the inclination —whether T Tau S is on the near or far side— and the origin of the outflow: is it associated with the optical star or with T Tau S, the more active object as suggested by its radio emission? No kinematic information is available from our observations, but the ionized outflow in the same direction indicates a velocity of ≈ 40 km s^{-1} (Böhm & Solf 1994) whereas the CO outflow suggests a velocity of about 15 km s^{-1} (Levreault 1988). We adopt an outflow velocity of 40 km s^{-1} for the H_2. The opening angle is assumed to be small ($\approx 5°$) as appears to be typical for outflows in young objects when imaged with high excitation lines (Bachiller & Gómez–González 1992).

The resulting trajectories of the outflow material are plotted in Fig. 2, where it is assumed that the outflow originates from T Tau S and that the inclination is such that this infrared

companion is on the far side. Clearly the outflow material fills a considerable part of the picture, similar to what is seen in the observations. The observed direction of the outflow close to the star is indeed almost perpendicular to the assumed orientation of the line of nodes.

The fact that other observations (Böhm & Solf 1994) show blue–shifted emission to the south of T Tau constrains the sign of the inclination, because it was noted above that the rotation of the circumstellar material is such that the west side is receding from the observer. It is tempting to identify the knot in the $v = 1 \rightarrow 0$ S(1) emission south of T Tau with the curl in the model trajectories. Note that the direction of this bend can then only be reproduced with the assumption that the outflow originates from T Tau S. The location of this knot was used to constrain the outflow velocity to ≈ 40 km s^{-1}. For larger inclinations similar models can be obtained by adopting lower values of the outflow velocity. Using 15 km s^{-1} as a minimal value, inclinations larger than $|i| = 30°$ appear to be excluded. The receding outflow is not observed as clearly, but it may be partly obscured by dust close to T Tau. Support for this model may be found in Skinner et al. (1994), who detected radio emission with an extension from T Tau S to the north–west with the same position angle as the H_2 emission.

A comparison between the model trajectories and the data may allow an order of magnitude estimate of the lifetime of the
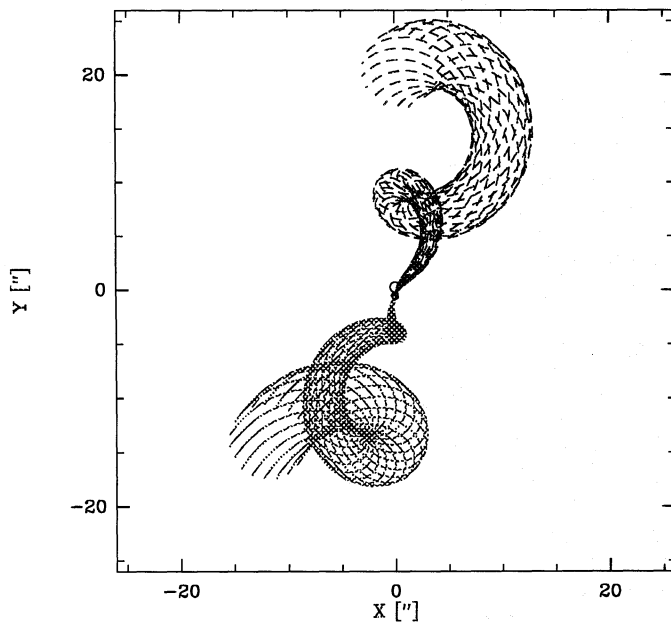
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Fig. 2. Ballistic model for the undisturbed outflow from T Tau S. The calculations have been restricted to material ejected in the last 1300 years. Blue–shifted emission is indicated by grey connected lines, red–shifted emission is drawn in dashed black.

excited gas in the outflow, if the bright emission south of T Tau is identified with the second bend of the flow. Since there is no trace of a third, it is estimated that the "cooling time" of the gas is of the order of two orbital periods, or 1440 years. This compares well with estimates of the cooling times for warm, moderately dense gas (e.g. Draine et al. 1983).

The proposed model is consistent with the observed large scale molecular outflow, which does not exhibit a clear bipolar distribution (Levreault 1988, Edwards & Snell 1982). A "precessing jet" was previously proposed for T Tau to explain the morphology of the optical nebulosities associated with T Tau by Schwartz (1990). The timescale for any precession mechanism is much longer than the direct reflection of the orbital motion we propose here (Fukue & Yokoo 1986). However, our model does not explain the morphology of the extended optical nebulosity in the western direction. Thus additional precession, as proposed by Schwartz (1990), may be needed to explain this nebulosity. Another possibility is a second outflow originating from T Tau N, which, because of the small inclination, may appear to have a different orientation. Such an outflow with a higher velocity and ionisation degree is present in the data discussed by Böhm & Solf (1994).

We conclude that many of the unusual characteristics of T Tau originate from the fact that we see a binary YSO with a special orientation; we suggest that T Tau is likely a relatively embedded YSO which would show a well collimated outflow when observed from a different angle. The pole–on geometry results in a low extinction to the stars which allows detection of vibrationally excited H_2 much closer than is commonly the case for other YSO's.

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