Outflows in S106 IR and Cep A East

P.R. Wesselius

SRON, P.O. Box 800, NL–9700 AV Groningen, The Netherlands

M.E. van den Ancker

Astronomical Institute "Anton Pannekoek", University of Amsterdam, Kruislaan 403, NL–1098 SJ Amsterdam, The Netherlands

A.G.G.M. Tielens

NASA Ames Research Center, MS 245-3, Moffett Field, CA 94035, U.S.A., and SRON, P.O. Box 800, NL–9700 AV Groningen, The Netherlands

L.B.F.M. Waters

Astronomical Institute "Anton Pannekoek", University of Amsterdam, Kruislaan 403, NL–1098 SJ Amsterdam, The Netherlands

Abstract.

We discuss the results of infrared spectroscopy of pure rotational lines of H_2, as well as several fine-structure lines for two embedded intermediate-mass Young Stellar Objects (YSO's): S106 IR and Cep A East. Excitation temperatures and masses are 490 and 740 K and 0.04 and 0.007 $M_\odot$ for S106 and Cep A, respectively. The bulk of the H_2 (several $M_\odot$ are expected) must be cooler than a few hundred Kelvin. We conclude that the infrared spectrum of S106 IR is dominated by PDR emission while that of Cep A East has a large shock component.

1. Introduction

The infrared emission line spectrum of Young Stellar Objects (YSO's) is dominated by the interaction of the central object with the remnants of the cloud from which it formed. Intense ultraviolet radiation from the central star and possibly from accretion causes dissociation of dust and molecular material close to the YSO and ionizes much of the atomic material, giving rise to typical nebular and recombination lines. The strong stellar wind, often collimated into a bipolar outflow, will cause a shock wave as it penetrates in the surrounding molecular cloud, warming the post-shock gas to sufficient temperatures to cause strong molecular and ionic emission. We analyze Infrared Space Observatory (ISO) Short Wavelength Spectrometer (SWS) data on infrared fine-structure lines and molecular hydrogen emission from two such YSO's: the central re-

Table 1. Observed and extinction-corrected line fluxes (in 10^{-14} W m^{-2}).

Line	λ [μm]	S106 IR Obs.	S106 IR Ext. corr.	Cep A East Obs.	Cep A East Ext. Corr.
H_2 0–0 S(0)	28.2188	–	–	–	–
H_2 0–0 S(1)	17.0348	0.81	1.30	0.09	0.20
H_2 0–0 S(2)	12.2786	–	–	–	–
H_2 0–0 S(3)	9.6649	0.33	1.25	0.10	0.92
H_2 0–0 S(4)	8.0251	0.19	0.30	0.17	0.36
H_2 0–0 S(5)	6.9095	0.21	0.27	0.31	0.47
H_2 0–0 S(6)	6.1086	–	–	0.09	0.15
H_2 0–0 S(7)	5.5112	–	–	0.21	0.36
H_2 0–0 S(8)	5.0531	–	–	0.05	0.09
H_2 0–0 S(9)	4.6946	–	–	0.08	0.16
H_2 0–0 S(10)	4.4099	–	–	0.06	0.13
H_2 0–0 S(11)	4.1813	–	–	–	–
[Fe I] ($^5D_4$–$^5D_3$)	24.0423	–	–	–	–
[Fe I] ($^5D_3$–$^5D_2$)	34.7133	–	–	–	–
[Fe II] ($^4F_{9/2}$–$^4F_{7/2}$)	17.9410	0.15	0.25	0.05	0.12
[Fe II] ($^6D_{9/2}$–$^6D_{7/2}$)	25.9882	3.27	4.35	0.11	0.18
[Fe II] ($^6D_{7/2}$–$^6D_{5/2}$)	35.3491	1.26	1.50	0.24	0.32
[S I] ($^3P_2$–$^3P_1$)	25.2490	–	–	0.41	0.68
[Si II] ($^2P_{1/2}$–$^2P_{3/2}$)	34.8140	16.7	20.0	0.51	0.69

gion of the bipolar nebula S106, and the eastern part of the complex molecular outflow source Cep A.

2. Shocks and PDR's

Molecular clouds irradiated by far-ultraviolet (FUV) photons are known as photodissociation regions (PDR's). The gas in their surface regions reaches temperatures of typically 500 K, making it possible to collisionally excite the low-lying pure rotational levels of molecular hydrogen, provided that the region is dense enough and there is sufficient incident FUV flux.

There exist two kinds of shocks: J(ump) shocks or C(ontinuous) shocks, depending on whether sufficient temperatures are reached to dissociate the molecular material in the shock front. In C shocks the physical conditions change more gradually from their pre- to post-shock values than in J shocks. If the temperatures in a C shock become sufficiently high to start to dissociate molecules, the cooling via molecular lines diminishes, and the shock temperature increases until the C shock converts into a J shock. J shocks usually have a shock velocity larger than 40 km s^{-1}, whereas slower shocks are usually of C type.

3. Observations

SWS short grating scans (AOT 2) of selected molecular hydrogen and atomic fine-structure lines of S106 IR and Cep A East were obtained. Data were reduced using the standard 'pipeline' software, but with manual checks of the level of dark currents. Scanned lines and measured line fluxes for detected lines are

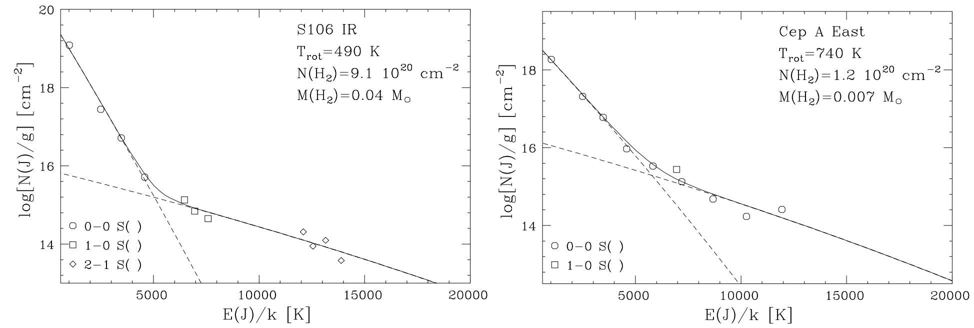

Figure 1. H_2 excitation diagrams for S106 (left) and Cep A East (right). ISO observations of pure rotational lines are indicated by circles. Diamonds and squares indicate ground-based measurements of ro-vibrational lines from literature. The dotted lines show the Boltzmann distribution fits to the low-lying pure rotational lines, and to the lines with upper level energies above 5000 K. The solid line indicates the sum of both contributions

listed in Table 1. Probably the H_2 0–0 S(2) line escaped detection because of fringing problems in this part of the spectrum.

The SWS beam size varies with wavelength and is rather large with respect to the angular dimensions of YSO features. When a line is detected it is unclear whether it is emitted from the whole beam region or from a smaller source within it. The Cep A East observations are not even centered on the central source and it is likely that a large area contributes to the line emission. This makes comparison with model calculations problematic. Model column densities can only be compared to observed lower limits and even line ratios cannot always be used; only when the two lines that are compared have been observed with the same SWS beam. Fortunately, there are several such line pairs.

4. Molecular Hydrogen emission

¿From the H_2 line fluxes it is possible to calculate the apparent column densities of molecular hydrogen in the upper J levels, averaged over the SWS beam, after correcting the observed line fluxes for extinction using values of A_V of 24 and 40 for S106 IR and Cep A East, respectively (Eiroa et al. 1979; Felli et al. 1984). This correction is especially important for the 0–0 S(3) line at 9.66 μm, since it is affected by the silicate absorption feature in the extinction curve.

In Fig. 1 we plot the log of $N(\mathrm{J})/g$, the beam-averaged column density for a given J upper level divided by the statistical weight, versus the energy of the upper level. The statistical weight g used is a combination of rotational and nuclear spin components, assuming the high temperature equilibrium relative abundances of 3:1 for the ortho and para forms of H_2 (Burton et al. 1992). For a Boltzmann distribution, the slope of the points in such a plot is inversely proportional to the excitation temperature.

The column densities listed in Fig. 1 combined with the distances to S106 and Cep A of 600 and 690 pc (Staude et al. 1982; Mel'nikov et al. 1995), correspond to molecular hydrogen masses of 0.04 and 0.007 $M_\odot$. The fact that the points for ortho and para H_2 lie on the same line proves that our assumption on their relative abundances is correct.

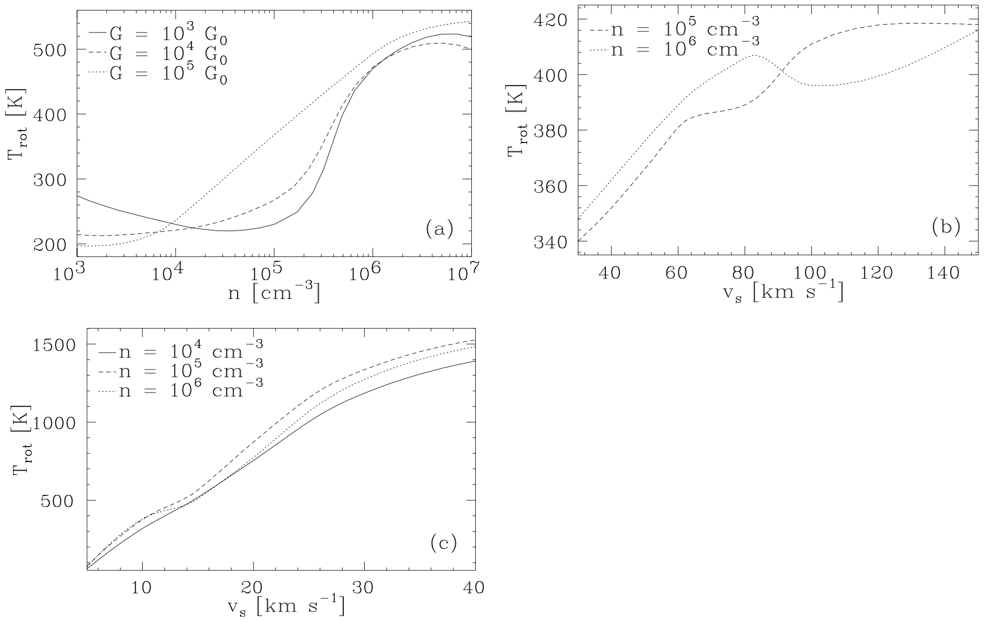

Figure 2. Theoretical relation between a) $T_{\rm rot}$ and n for PDR models, b) $T_{\rm rot}$ and v_s for J-shock models, and c) $T_{\rm rot}$ and v_s for C-shock models

The column densities of H_2 lines originating from upper levels higher than 5000 K deviate significantly from the leftmost dotted line in Fig. 1. In the case of S106, the relative location of the 1–0 and 2–1 S-lines in Fig. 1 is indicative of fluorescent excitation through UV pumping (Black & van Dishoeck 1987; Draine & Bertoldi 1996). A Boltzmann distribution fit to the higher energy levels (shown in Fig. 1) has thus no physical meaning.

Employing predictions of H_2 emission from PDR, J-shock and C-shock models by Burton et al. (1992), Hollenbach & McKee (1989) and Kaufman & Neufeld (1996), the excitation temperature $T_{\rm rot}$ for the low-lying pure rotational levels from these models as a function of density n and either incident FUV flux G (in units of the average interstellar FUV field G_0) or shock velocity v_s was determined (Fig. 2). The PDR and J-shock models predict a fairly small (200–540 K) range of resulting excitation temperatures, whereas for C shocks the range is much larger (100–1500 K). Furthermore, the resulting $T_{\rm rot}$ does not depend much on density, whereas for PDR's it does not depend much on G.

The S106 value of 490 K falls within the range of PDR- and C-shock model predictions, but is too high compared to the ones expected from J shocks. The higher temperature for Cep A (740 K) can only be reproduced by C-shock models. Therefore we tentatively conclude that a dense ($\geq 10^6$ cm^{-3}) PDR seems to be the best candidate to explain the observed H_2 emission in S106 IR and a slow (≈ 20 km s^{-1}) non-dissociative shock can explain the observed warm column of H_2 in Cep A East. The model column densities of H_2 should be higher than the beam-averaged observed values of Table 1, possibly indicating that only part of the beam area emits the lines.

5. Fine Structure Lines

Important constraints on the possible excitation mechanisms come from the observed fine structure lines. As a first step towards identifying the mechanism responsible for the observed emission we can look at the mere presence of certain lines. In contrast to both C and J shocks, PDR's do not produce significant quantities of [S I] emission (Tielens & Hollenbach 1985). C shocks can only contain trace fractions of ions and can therefore not explain the observed [Fe II] and [Si II] emission. Hence the starting hypothesis is that the observed fine-structure lines from S106 arise in a PDR, whereas those of Cep A originate in a J shock.

To be able to explain the observed surface brightness for the [Si II] line in S106, the Tielens & Hollenbach (1985) PDR models require a density higher than $\approx 10^5$ cm^{-3} and $G \geq 10^5$ G$_0$. Such a model PDR can also reproduce the observed ratios of [Si II] and the [Fe II] lines. The predicted intensities of [S I] and [Fe I] are sufficiently low to be undetectable, in agreement with the observations.

For Cep A the situation is more complicated. From the detection of the [S I] line at 25.25 μm, we know that either a J or C shock must be present. The detection of [Si II] and [Fe II] emission indicates a J shock or PDR. Thus it seems that the observed spectrum should be interpreted as caused by a J shock. Because we do not expect such a J shock to fill the SWS beam completely, line ratios may provide a more reliable diagnostic tool provided the aperture sizes are the same. To reproduce both the ratio of [Fe II] 26.0 μm to [S I] 25.2 μm and the ratio of [Fe II] 35.3 μm to [Si II] 34.8 μm with the Hollenbach & McKee (1989) J shock models requires either moderately dense (10^5 cm^{-3}) gas with a low (30 km s^{-1}) shock velocity or a high (10^6 cm^{-3}) density with a faster ($\approx$ 60 km s^{-1}) shock. To have the predicted [Fe I] emission sufficiently low to explain our non-detections of those, the dense, fast J-shock model is required. The predicted surface brightnesses in this regime are higher than those observed, in agreement with a shock only filling part of the SWS beam.

6. Discussion and Conclusions

For S106 IR the observed infrared H_2 emission and fine structure lines can be explained as arising in a PDR with $n \approx 10^6$ cm^{-3} and $G \approx 10^5$ G$_0$.

For Cep A East, J shocks cannot reproduce the observed H_2 emission, while its fine-structure lines can only be caused by a J shock. This contradiction and the absence of PAH emission in Cep A East (Hodapp & Eiroa 1989) indicates that a combination of J and C shocks is responsible for the observed emission in Cep A. This could be linked to the reported multiple episodes of outflow activity from the embedded source (Narayanan & Walker 1996). In the presence of both a J and a C shock, the [Si II] and [Fe II] emission would originate completely in the J shock, whereas both the C and the J shock would contribute to the observed [S I] and H_2 spectra. The Cep A East C and J shocks need shock velocities of about 20 and 60 km s^{-1} respectively, to explain the infrared line-spectrum. For both shocks we found the same densities, $\approx 10^6$ cm^{-3}.

The observed H_2 masses in both S106 and Cep A amount only to a few hundredths of $M_\odot$, whereas several solar masses of H_2 are expected in these star forming regions. This implies that the bulk of the molecular hydrogen must be much cooler than that observed here.

The values of density and strength of FUV field are rather high. They are based on the use of models in which the assumed heating processes are rather uncertain. In fact, when density and strength of FUV field could be determined otherwise the molecular hydrogen temperature could be used to assess the overall heating of the H_2.

The differences between the environment of these two massive embedded YSO's, S106 and Cep A, are remarkable. In S106 the stellar wind and UV radiation of the exciting source have cleared and excited a sufficiently large region to create strong PDR emission, whereas in the case of Cep A, the central source is still heavily embedded and we observe the interaction of its outflow with its surroundings. The difference between these two sources is interpreted by us as due to a different evolutionary status, with Cep A being the younger of the two. In due time, Cep A could clear its immediate surroundings, ionize the hydrogen, and evolve into a bipolar nebula quite similar to S106.

Acknowledgments. LBFMW acknowledges financial support from the Royal Netherlands Academy of Arts and Sciences, and through an NWO *Pionier* grant.

References

Black, F.H., & van Dishoeck. E.F. 1987, ApJ, 322, 412

Burton, M.G., Hollenbach, D.J., & Tielens, A.G.G.M. 1992, ApJ, 399, 563

Draine, B.T., & Bertoldi, F. 1996, ApJ, 468, 269

Eiroa, C., Elsässer, H., & Lahulla, J.F. 1979, A&A, 74, 89

Felli, M., Staude, H.J., Reddmann, T., Massi, M., Eiroa, C., Hefele, H., Neckel, T., & Panagia, N. 1984, A&A, 135, 261

Hodapp, K.W., & Eiroa, C. 1989, AJ, 97, 166

Hollenbach, D.J., & McKee, C.F. 1989, ApJ, 342, 306

Kaufman, M.J., & Neufeld, D.A. 1996, ApJ, 456, 611

Mel'nikov, S.Y., Shevchenko, V.S., & Grankin, K.N. 1995, Astron. Rep., 39, 42

Narayanan, G., & Walker, C.F. 1996, ApJ, 466, 844

Staude, H.J., Lenzen, R., Dyck, H.M., & Schmidt, G.D. 1982, ApJ, 255, 95

Tielens, A.G.G.M., & Hollenbach, D.J. 1985, ApJ, 291, 722