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# SWS $H_2$ observations in the BD+40°4124 group*

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**Abstract.** We report the detection of pure rotational lines of $H_2$ observed in the direction of three young stellar objects in the BD+40°4124 group, with the short-wavelength spectrometer (SWS) on board ISO. The rotational population distributions of all three stars are consistent with a thermal distribution. The derived kinetic temperatures are $\approx$ 500 K for BD+40°4124 and LkH$\alpha$ 224 and $\approx$ 800 K for LkH$\alpha$ 225. The amounts of molecular hydrogen detected are 0.01 to 0.04 $M_\odot$. The relative abundances of ortho- and para-hydrogen are consistent with a high temperature equilibrium distribution. We conclude that the molecular hydrogen emission in all three regions appears to lie behind approximately 10–25$^{\rm m}$ of visual extinction and is probably not directly associated with any of the optical sources.

**Key words:** sircumstellar matter – stars: formation – stars: pre-main sequence – infrared: stars

## 1. Introduction

BD+40°4124 (= V1685 Cyg) is one of the original Ae/Be stars with associated nebulosity studied by Herbig (1960). It is located in the Cygnus arm at a distance of about one kpc and is the optically brightest member of a small group of young stars that includes LkH$\alpha$ 224 (= V1686 Cyg) and LkH$\alpha$ 225 (= V1318 Cyg), all of which have infrared excesses (Strom et al. 1972). These objects were also studied by Cohen (1972) who concluded that these stars must be very young. The IRAS survey showed a powerful source at this position, but the IRAS positional uncertainty does not allow to assign the flux to one of these three objects; indirect arguments may be used (Hillenbrand et al. 1992; Weaver & Jones 1992).

Aspin et al. (1994) have shown LkH$\alpha$ 225 to be a triple system oriented north-south with the most northern and southern components separated by 5″. They also obtained an 800 $\mu$m continuum map of the region that clearly peaks on LkH$\alpha$ 225. Photometric and spectroscopic observations by the same authors strongly suggest that the southern component of LkH$\alpha$ 225 is dominant in the mid-infrared. In particular, it is the brightest member of the group at 10 $\mu$m. Interestingly, their K-band spectrum of LkH$\alpha$ 225-South shows strong vibration-emission lines of molecular hydrogen. Aspin et al. (1994) estimate the total luminosity of this object to be $\approx$ 1600 $L_\odot$.

Palla et al. (1994) obtained near infrared, CO, $C^{18}O$, CS, and $H_2O$ maser observations on the group. Their high resolution VLA observations show that the maser source is clearly associated with LkH$\alpha$ 225-South. Moreover, a density concentration in the molecular cloud (as evidenced by CS J=5—4 emission) and a CO outflow are both associated with LkH$\alpha$ 225. In their model, LkH$\alpha$ 225 is at the center of a dense molecular core of mass $\approx$ 280 $M_\odot$, while BD+40°4124 lies near the periphery.

Hillenbrand et al. (1995) have obtained intermediate resolution optical spectra for all of the visible sources in the group. They classify BD+40°4124 as B2 Ve, LkH$\alpha$ 224 as B5 Ve, and both LkH$\alpha$ 225-North and South as mid-A to Fe. However, the luminosity of LkH$\alpha$ 255-South of 1600 $L_\odot$ (Aspin et al. 1994) puts this object well in the region of intermediate-mass stars.

In this paper, we present some initial results of ISO SWS observations towards three objects of the BD+40°4124 group. These spectroscopic observations allow us to probe the physical conditions in the vicinity of the star, and help restrict the applicable models for the infrared emission mechanisms.

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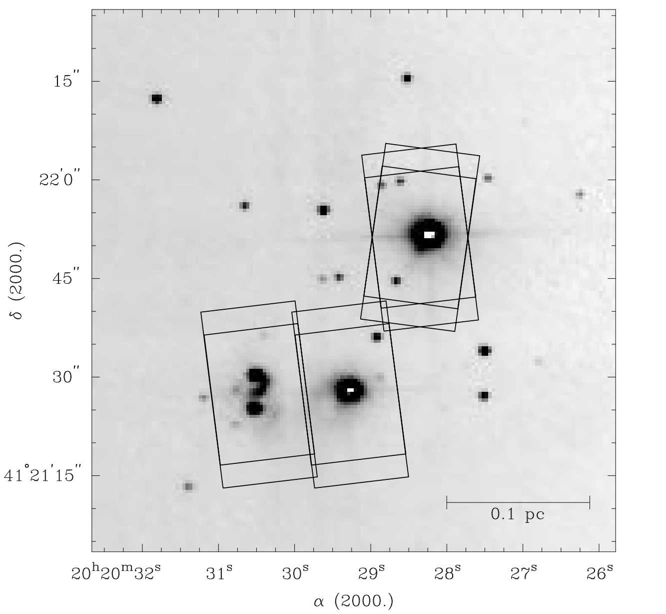


**Fig. 1.** SWS aperture positions for our measurements of (from right to left) BD+40°4124, LkH$\alpha$ 224 and LkH$\alpha$ 225 superimposed on a K-band image of the region. The large rectangles indicate the apertures for SWS bands 3A–3D (12.0–27.5 $\mu$m), whereas the smaller ones show the apertures for bands 1A–2C (2.4–12.0 $\mu$m)

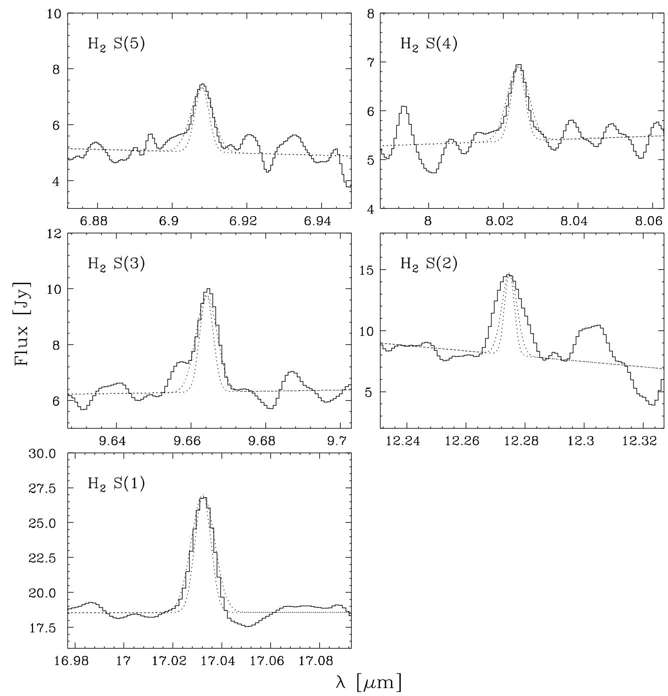


**Fig. 2.** Rotational $H_2$ lines detected in LkH$\alpha$ 224. Just for comparison, dotted lines are shown, indicate the instrumental resolutions for a point source and an extended source; for the flux determination the actually observed profile was used.

## 2. Observations

In revolution 142 of ISO we observed LkH$\alpha$ 224 (at JD 2450181.960), LkH$\alpha$ 225 (JD 2450181.996) and BD+40°4124 (JD 2450182.037) with the SWS using observing mode 'S02'. A description of the SWS instrument and its observing modes is given elsewhere in this volume of A&A by de Graauw et al., whereas a full description of ISO itself is given by Kessler et al.. The employed SWS photometric and wavelength calibrations are also described elsewhere in this volume, by Schaeidt et al. and Valentijn et al., respectively. Each observation took about 45 minutes. BD+40°4124 was also observed in revolution 159 (at JD 2450198.635); both observations were combined.

Since SWS uses apertures that are fairly large compared to the separation of sources in most star forming regions, some caution is appropriate in interpreting such measurements. We created a plot with the positions of the SWS apertures, overlaid on a K-band image of the region (Hillenbrand, 1996, Fig. 1). Each aperture area just covers one of the three major sources which presumably are responsible for the $H_2$ emission.

Of the pure rotational lines of $H_2$ we have only scanned the spectral regions of the lines S(0) to S(7), S(10), S(11) using 'S02'. This SWS observing mode makes it possible to detect narrow emission lines. The present dynamic range allows to detect a line flux of $\approx$ 5% or more of the continuum, provided the continuum level is at $\approx$ 5 Jy or more. Line fluxes can be determined with an accuracy of about 30 % (Schaeidt et al. 1996). Because of instrumental problems (fringing) the S(2) line at 12.28 $\mu$m is more difficult to detect and measure (the one for LkH$\alpha$ 225 should be quite strong, but is lost in this fringing). Detected lines and measured line fluxes are listed in Table 1. Note that the detection of the S(4) line in BD+40°4124 is marginal, however. Plots of all detected lines, rebinned to a resolution $\lambda/\Delta\lambda$ of 3000 with an oversampling factor of four, are given in Figs. 2–4. The observed shape of the line profiles has rather large uncertainties at this stage of the data reduction: the broadening and P-Cygni profiles seen should be considered as artefacts at present.

The lines S(10) and S(11) were not detected in any of the objects. An upper limit on these line strengths, assuming they are unresolved, is $5 \times 10^{-16}$ W m$^{-2}$.

## 3. Discussion

That LkH$\alpha$ 225 is the dominant source of the BD+40°4124 group, as concluded by Aspin et al. (1994), is consistent with the continuum strength of these three objects: the SWS continuum in the range 5.5–17 $\mu$m is approximately 5 times higher at the position of LkH$\alpha$ 225 than at the two other pointings.

¿From the line fluxes listed in Table 1 it is possible to calculate the column densities in the upper J levels, averaged over the SWS beam, by using the A coefficients from Turner et al. (1977). For these objects, the extinction correction is particularly important for the S(3) line at 9.66 $\mu$m which is in the silicate absorption band. Aspin et al. (1994) derive an $A_V$ of 25 $\pm$ 9 magnitudes for LkH$\alpha$ 225-South, which would correspond to over one magnitude of extinction at the wavelength

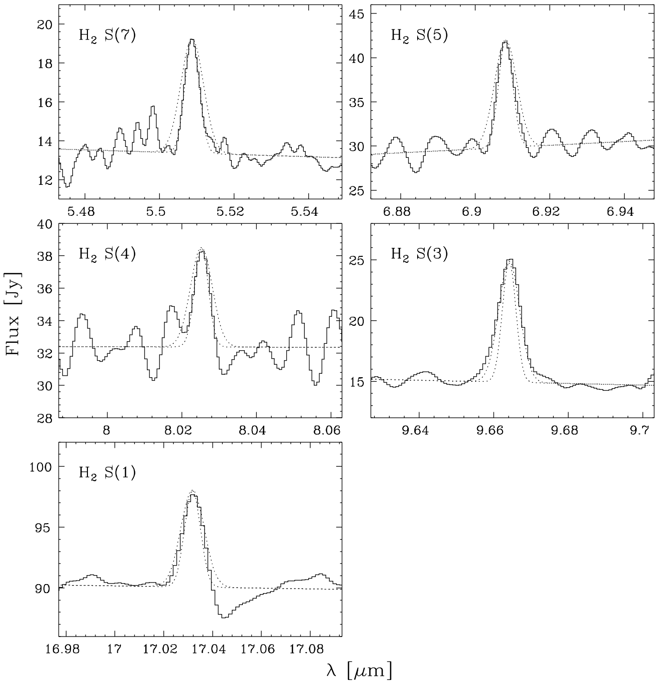


**Fig. 3.** The same as Fig. 2 for LkH$\alpha$ 225

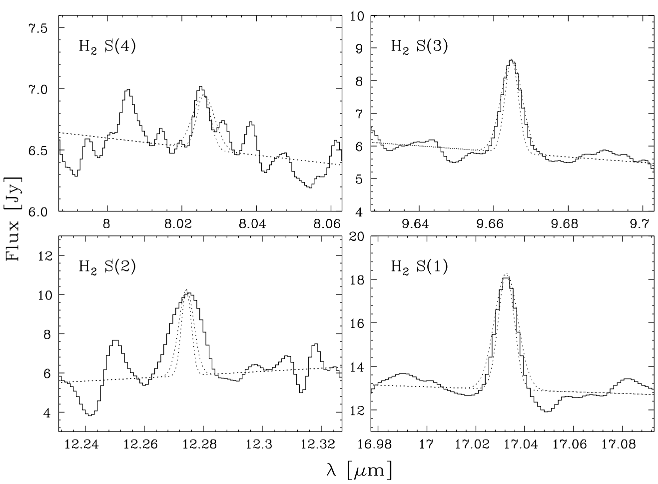


**Fig. 4.** The same as Fig. 2 for BD+40°4124

of the line. An examination of the continuum levels observed by the SWS is consistent with this level of extinction. Using the observed silicate absorption, we have applied an extinction correction with $A_V$ = 25$^{\rm m}$ for LkH$\alpha$ 225, 20$^{\rm m}$ for LkH$\alpha$ 224 and 10$^{\rm m}$ for BD+40°4124. For the other wavelengths we have adopted a 1/$\lambda$ extinction law.

A useful representation of the data is to plot the log of $N$(J)$/g$, the column density for a given J upper level divided by the statistical weight, versus the energy of the upper level (Fig. 5). Here the statistical weight is the combination of the rotational and nuclear spin components. We have assumed the high temperature equilibrium relative abundances of 3:1 for the ortho and para forms of $H_2$ . For a Boltzmann distribution, the slope of

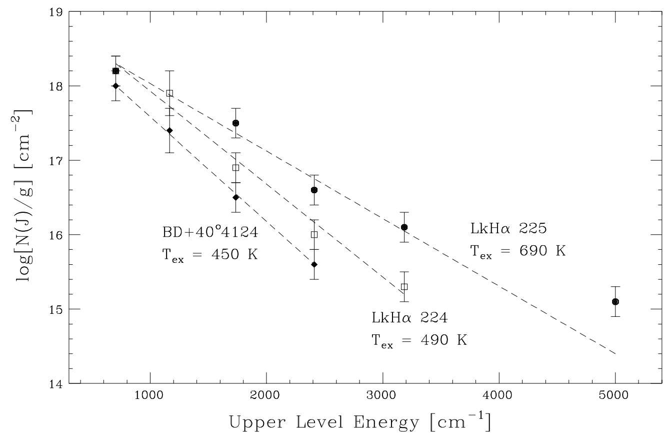


**Fig. 5.** $H_2$ excitation diagram for the BD+40°4124 objects

**Table 1.** Observed $H_2$ line fluxes (errors ≈ 30 %; 50 % for ':')

| Object | Line | $\lambda_c$ [$\mu$m] | Line Flux [ $10^{-16}$ W m$^{-2}$] | $M$ ($H_2$) [$M_\odot$] |
|---|---|---|---|---|
| LkH$\alpha$ 224 | S(5) | 6.9084(5) | 7.9 | 0.04 |
| | S(4) | 8.0241(5) | 5.2 | 0.02 |
| | S(3) | 9.6648(5) | 11.0 | 0.02 |
| | S(2) | 12.2747(8) | 21.5: | 0.05 |
| | S(1) | 17.0326(10) | 13.0 | 0.02 |
| LkH$\alpha$ 225 | S(7) | 5.5087(4) | 39.2 | 0.3 |
| | S(5) | 6.9080(5) | 48.8 | 0.02 |
| | S(4) | 8.0257(5) | 18.3 | 0.02 |
| | S(3) | 9.6643(5) | 28.4 | 0.02 |
| | S(1) | 17.0324(10) | 13.2 | 0.02 |
| BD+40°4124 | S(4) | 8.0254(8) | 2.2: | 0.02 |
| | S(3) | 9.6648(5) | 8.3 | 0.01 |
| | S(2) | 12.2752(8) | 6.1: | 0.01 |
| | S(1) | 17.0325(10) | 6.9 | 0.01 |

this plot is inversely proportional to the excitation temperature. Since the A-coefficients for the $H_2$ lines are quite small, these lines are optically thin and the excitation temperature will be close to the kinetic temperature of the gas.

Figure 5 supports this interpretation since all the line intensities for a given star can be well fit with a single temperature. That the points for ortho and para $H_2$ lie on the same line proves that our assumption on their relative abundances is correct. Other processes, such as UV pumping or the $H_2$ formation process, can affect the population distribution as well, but the data presented here show little evidence for this. Observations of higher excitation rotational lines and/or vibration-rotation lines are needed to better constrain these contributions.

For BD+40°4124 and LkH$\alpha$ 224, the derived excitation temperature is approximately 500 K. The temperature of the $H_2$ gas for LkH$\alpha$ 225 is significantly higher, at nearly 800 K, if all the observed lines are considered. Just using the lowest four lines provides a significantly better fit (at 690 K); S(7) lies well above the fitted line. The excess emission in the highest J line could be the result of an additional contribution from formation-pumped emission. Additional observations of higher J-level transitions will be necessary to constrain the models.

Using the observed fluxes, assuming a thermal distribution of the low J levels, and correcting for the proposed extinction towards each of the objects, the average column density of the warm $H_2$ within the SWS beam has been estimated. Table 1 lists the results of this calculation for each line observed. The calculated values lie between 0.01 and 0.05 $M_\odot$ except for the deviating S(7) line of LkH$\alpha$ 225.

The rotational $H_2$ emission lines can originate from various distinct zones around the young stellar object (YSO), each excited by different processes. These include a scenario in which the photosphere of a circumstellar disk gets radiatively heated by the star and hence gives rise to emission rather than absorption lines. Alternatively, these lines may probe the inner (collapsing) envelope of the YSO where collisions with warm dust keep the gas to temperatures of 400–800 K. Radiation from the YSO may also create a photon-dominated region (PDR) in the surrounding molecular cloud where the gas is heated by photoelectrons ejected from grains (Burton et al. 1992). The required densities and FUV fields locate the PDR then fairly close to the YSO as well. Perhaps most likely, the $H_2$ emission originates in a very weak C-type shock wave driven into the surrounding molecular cloud by stellar outflows. Support for this interpretation comes from the paper by Aspin et al. (1994), who concluded that a source of shock-excitation must be present in the BD+40°4124 region.

Under the right conditions, all of these types of processes can give rise to very similar $H_2$ rotational emission spectra. Only complementary observations will be able to distinguish between them. Thus, circumstellar disks will have characteristic recombination line spectra, collapsing envelopes will radiate copiously in $H_2O$ rotational lines, PDRs and shocks emit strong fine structure lines of [O I] and [C II] as well as rovibrational $H_2$ lines but their detailed spectra are quite distinct.

## 4. Conclusions

The SWS on ISO has been used to observe pure rotational lines of $H_2$ towards three young stellar objects in the BD+40°4124 group. The rotational population distributions are consistent with a thermal distribution in all three sources. The relative abundances of ortho and para $H_2$ are consistent with a high temperature equilibrium distribution. The flux in the S(3) line of LkH$\alpha$ 225 has to be corrected for $\approx$ 1.3 magnitudes of extinction due to the silicate absorption feature. Hence, the $H_2$ emission region for this embedded source appears to lie behind approximately $25^{\rm m}$ of $A_V$ and could be associated with LkH$\alpha$ 225-South. For LkH$\alpha$ 224 and BD+40°4124 the pure rotational $H_2$ lines seem to be obscured by 20 and 10 magnitudes of visual extinction, respectively. An origin of these lines in a heavily obscured circumstellar disk seems unlikely because of the observed single temperature distribution and the very small amounts of $H_2$ involved. Therefore, these $H_2$ lines are probably not directly associated with the optical sources. The $H_2$ involved amounts to 0.01 to 0.04 $M_\odot$.

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