Fast spectroscopic variations on rapidly rotating, cool dwarfs – III. Masses of circumstellar absorbing clouds on AB Doradus*

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Accepted 1990 June 13. Received 1990 June 12; in original form 1990 January 15

SUMMARY
We present new time-resolved Hα, Ca II H and K and Mg II h and k spectra of the rapidly rotating K0 dwarf star AB Doradus ( = HD 36705). The transient absorption features seen in the Hα line are also present in the Ca II and Mg II resonance lines. New techniques are developed for measuring the average strength of the line absorption along lines-of-sight intersecting the cloud. These techniques also give a measure of the projected cloud area. The strength of the resonance-line absorption provides useful new constraints on the column densities, projected surface areas, temperatures and internal turbulent velocity dispersions of the circumstellar clouds producing the absorption features. At any given time the star appears to be surrounded by between 5 and 20 clouds with masses in the range 2-6 x 10^17 g. The clouds appear to have turbulent internal velocity dispersions of order 3-20 km s^-1, comparable with the random velocities of discrete filamentary structures in solar quiescent prominences. Night-to-night changes in the amount of Ca II resonance line absorption can be explained by changes in the amplitude of turbulent motions in the clouds. The corresponding changes in the total energy of the internal motions are of order 10^29 erg per cloud. Changes of this magnitude could easily be activated by the frequent energetic (~ 10^{34} erg) X-ray flares seen on this star.

1 INTRODUCTION
AB Doradus is a young, spotted K0 dwarf with an unusually short axial rotation period of 0.514 d (Pakull 1981). It is a flaring coronal X-ray source (Collier Cameron et al. 1988; Vilhu & Linsky 1987). Optical and UV spectra show strong chromospheric and transition region line emission (Vilhu, Gustafsson & Edvardsson 1987; Rucinski 1985), indicating high levels of magnetic activity in the star’s outer atmosphere. Innis, Thompson & Coates (1986) suggested on the basis of its space motion that it is a likely member of the Pleiades Moving Group (also known as the Local Association: Eggen 1973, 1975, 1983a,b). This implies that AB Dor is similar in age to the Pleiades cluster. This is supported by its high lithium abundance (Rucinski 1982) and the existence of a population of similarly rapidly rotating and magnetically active K dwarfs in the Pleiades cluster (van Leeuwen & Alphenaar 1983; van Leeuwen, Alphenaar & Meys 1987; Stauffer et al. 1984; Stauffer & Hartmann 1987).

In earlier papers in this series we discussed the properties of a system of prominence-like condensations of mainly neutral material, located between 3 and 10 stellar radii from the rotation axis of AB Dor and trapped in corotation with the star by the stellar magnetic field. The clouds were first discovered as transient absorption features in Hα (Robinson & Collier Cameron 1986; Collier Cameron & Robinson 1989a – Paper I). The absorption transients are produced...
when clouds pass between the observer and the stellar disc, scattering chromospheric Hα photons out of the line-of-sight. New clouds appear to form at the rate of one or two per day, just outside the Keplerian corotation radius, and subsequently move outwards until they finally escape from radial magnetic confinement, at least 10 $R_\ast$ from the rotation axis (Collier Cameron & Robinson 1989b - Paper II).

The specific angular momentum of the escaping cloud material is clearly high, and suggests that the cloud ejection process could contribute significantly to AB Dor's rotational braking rate. Observations in Hα alone do not, however, provide very tight constraints on the cloud masses, since the population of the lower state of the transition depends critically on both the temperature and density in the cloud interior. The Ca II and Mg II resonance lines are much better suited to determining the cloud column densities, but time-resolved spectroscopic studies of the Ca II H and K line profiles were not possible until dye-coated CCD detectors with extended blue response became widely available.

In the present paper we report the results of a coordinated programme of observations of AB Doradus made during 1988 December. We obtained high-dispersion, time-resolved Hα and Ca II H and K spectra at the European Southern Observatory (ESO) and the Anglo-Australian Observatory, and high-dispersion Mg II h and k spectra with the International Ultraviolet Explorer (IUE) satellite. In Section 2 we summarize the observations and data reduction techniques used, and in Sections 3 and 4 we describe the data analysis methods and absorption line profile synthesis used to constrain the projected areas, column densities, temperatures and internal velocity dispersions of the clouds. The implications for the masses and internal structure of the clouds are discussed in Section 5.

2 OBSERVATIONS AND DATA REDUCTION

2.1 Observing strategy

The programme of IUE, AAT and ESO observations of AB Dor undertaken during 1988 December is summarized in the journal of observations (Table 1). Of the four nights allocated to the programme at the AAT (December 16 to 19) only one (December 18) was lost due to poor weather, although the data quality during first half of the night of December 17 was degraded by variable cloud cover. The two ESA IUE shifts on 1988 December 17 and 19 coincided with the hours of darkness at the AAT. Within the limits imposed by spacecraft temperature constraints and camera readout and preparation, the high-resolution LWP exposures of the Mg II h and k region were made at stellar rotation phases where well-defined absorption transients or clear patches had been observed in Hα at the AAT on December 16 and 17. Ca II H and K observations were interleaved with the Hα observations on December 19, the last night of the AAT run.

All three nights of the ESO programme (December 21 to 23) were clear. The first night was devoted to continuous monitoring of the Hα profile, and the second to continuous monitoring of the Ca II H and K region. On the last night of the ESO run, Hα and Ca II H and K spectra were interleaved. During the three US IUE shifts on December 24 and 25, alternating LWP and SWP exposures were made, covering the full stellar rotation cycle.

2.2 AAT instrument configuration

The AAT spectra were obtained with the new UCL échelle spectrograph (UCLES: Walker & Diego 1985), at the coudé focus of the 3.9-m Anglo-Australian Telescope. The 31 lines mm$^{-1}$ échelle grating was used with the 70-cm camera and a liquid nitrogen-cooled, dye-coated GEC CCD as detector, giving a dispersion of 2.7 km s$^{-1}$ per 22 pm pixel in the dispersion direction. A slit width of 1.3 arcsec gave an instrumental profile with full width at half maximum intensity of 2.8 pixel, or 7.5 km s$^{-1}$. During times of poor seeing, a focal reducer (Diego & Walker 1985) was used to increase throughput by opening the slit width to 1.7 arcsec, while maintaining the same resolution at the detector. The CCD chip was binned by a factor of 4 in the slit direction, to reduce both readout noise and chip readout time. The exposure times used were 150 s for all Hα exposures, and 300 s for Ca II H and K.

2.3 ESO instrument configuration

The ESO spectra were obtained with the Cassegrain Échelle Spectrograph (CASPEC; Pasquini & D'Odorico 1989) on the 3.6-m telescope at La Silla. A 31.6 lines mm$^{-1}$ grating was used on the first night (1988 December 21 UT) in the red range centred at 6250 Å. A 52 lines mm$^{-1}$ grating was used on the second night in the blue range centred at 4200 Å. On the third night the 31.6 lines mm$^{-1}$ was used again, alternating between the blue and red ranges. The CASPEC échelle spectra range covers around 1000 Å at once, allowing features other than the prime lines (Hα and Ca II H and K) to be observed. The light is focused by a 291-mm camera on to a Thomson CCD detector with 1024x660 15 µm pixel. A slit width equivalent to 1.5 arcsec allowed an instrumental spectral resolution of 30 000 or 10 km s$^{-1}$. The seeing ranged between 1 to 1.5 arcsec and the weather was photometric during the ESO observing period. The whole CCD chip was read unbinned, using an exposure time of 300 s for all AB Dor frames, with a time lag of 50–60 s between exposures. The pixel to pixel response and wave-
length calibration were determined by using a quartz flat-field and a Thorium–Argon (Th–Ar) lamp.

2.4 IUE instrument configuration

IUE (Boggess et al. 1978) high-resolution spectra were taken through the large aperture (5 × 10 arcsec) with the Long Wavelength Prime camera covering the Mg II h and k emission lines. The VILSPA ground station near Madrid, Spain was used for the observations on 1988 December 17 and 19; the images were received at Goddard Space Flight Center in Greenbelt, Maryland in the United States on 1988 December 25 and 26. Exposure times were generally 40 min in duration, although exceptionally they were varied to 35 or 60 min (see Table 6). These provided reasonably exposed emission lines while avoiding too much smearing of features varying in wavelength during the exposure. The continuum is weak but visible. The spectral resolution of this observing configuration is 0.17 Å (18 km s⁻¹).

2.5 Data reduction: Hα and Ca II spectra

The échelle spectra from both UCLES and CASPEC were reduced at the RGO node of the UK STARLINK network. The data were extracted and calibrated using the AAO/MaTTech échelle reduction routines incorporated in the figaro package. After flat-fielding and extraction, each individual échelle order was written into a single row of a two-dimensional dynamic spectrum. Th–Ar arc exposures provided the wavelength calibration for both the AAT and ESO spectra. Each dynamic spectrum was rebinned to equal increments in log wavelength, with a velocity increment per pixel of 2.7 km s⁻¹. Finally, each row in the dynamic spectrum was corrected for low-frequency variations in continuum shape using a polynomial fit to a set of continuum windows. The Hα spectra were normalized to a continuum level set at unity. Because of the difficulty of locating the continuum in the blue part of the spectrum, the Ca II H and K spectra were normalized to a mean value of 1.0 over the wavelength range 3925.0 to 3975.0 Å. Sample Hα and Ca II H and K spectra are shown in Fig. 1.

2.6 Data reduction: Mg II spectra

The data sets from VILSPA and Goddard were extracted at their institute of origin using standard procedures. Both data sets were calibrated using the RDAF routine calibration. Both Mg II lines are overlayed by a narrow interstellar line, for whose absorption one must correct before measuring the flux. It was assumed that the interstellar absorption was

![Figure 1](image-url)
Figure 1 - continued

1988 Dec 22 05:05 to 06:04 Ca II H + He reference spectrum

1988 Dec 22 05:05 to 06:04 Ca II K

1988 Dec 22 05:05 to 06:04 Ca II H + He

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unresolved, so that each Mg II line could be fit by the function

\[ F(\lambda) = F(\lambda_0) + A_e \exp[-z^2(\lambda)] - F(\lambda_0) - \frac{W_0}{\sigma_c \sqrt{\pi}} \exp[-z^2(\lambda)]. \]  

(1)

Here, \( F(\lambda_0) \) is the continuum flux, which was fit as a second-order polynomial. \( A_e \) is the amplitude of the emission Gaussian. \( F(\lambda_0) \) is the value of the underlying stellar monochromatic flux at the wavelength \( \lambda_0 \), of the interstellar absorption line, and (ignoring the contribution of the continuum) is given approximately by \( F(\lambda_0) = A_e \exp[-z^2(\lambda_0)] \). \( W_0 \) is the equivalent width in angstroms of the interstellar line absorption and \( \sigma_c \) is the width of the instrumental profile, treated here as a Gaussian. We also use the notation

\[ z_e(\lambda) = \frac{\lambda - \lambda_0}{\sigma_e}, \]  

(2)

\[ z_0(\lambda) = \frac{\lambda - \lambda_0}{\sigma_0}, \]  

(3)

where \( \lambda_0 \) is the wavelength of the emission Gaussian. As the equivalent width of the interstellar absorption and the instrumental resolution must be the same for all exposures, the lines from all exposures should be fit simultaneously. In practice, all of the \( k \) lines were fit simultaneously, and all the \( h \) lines were fit simultaneously, but the whole set of lines were never fit as one batch. The equivalent widths of the interstellar lines and the instrumental resolutions from the two different fits were quite similar.

The fitting was done with a modified amoeba algorithm (Press et al. 1986; Kuntz 1990, in preparation). Uncertainties determined for the calculated quantities are the most extreme values of those quantities for which the chi square of the fit (at the extreme value of the calculated quantity) minus the best possible chi square for the fit is unity. The algorithm used to determine uncertainties is described in full in Kuntz (1990, in preparation).

The fluxes from the Mg II lines were measured in two ways. First, the fitted continuum was subtracted from the observed profile, and the result was integrated over a 3.4 Å (i.e. ±180 km s\(^{-1}\)) window centred on the line to give the total observed line flux. The flux absorbed in the interstellar line \( F(\lambda_0) \) was calculated from the multiple Gaussian fit. In general this 'missing' flux is expected to change from spectrum to spectrum: although the equivalent width \( W_0 \) of the interstellar feature should remain constant, the underlying monochromatic stellar flux \( F(\lambda_0) \) of the wavelength of the interstellar line will vary with time. This 'missing' flux was added to the observed line flux to give a line flux corrected for the effects of interstellar absorption. Secondly, we tried using the area under the fitted Gaussian emission profile to represent the intrinsic line flux. This would automatically compensate for interstellar absorption if the chromospheric line had a Gaussian profile. The measured flux (minus fitted continuum), the fitted absorbed flux, the corrected measured flux and the fitted emission flux are listed for each spectrum in Table 2.

The two methods do not agree as well as one would like. The ratio of the quantity as measured by the second method to that measured by the first will always be greater than unity, and will increase with increasing noise. This is due to the fitted flux being a function of the width of the emission Gaussian, which will always be larger than it should be due to the noise in the wings. The quantity derived by the first method (labelled 'Corrected flux' in Table 2) is therefore to be preferred.

### 3 MEASURING THE CLOUD ABSORPTION PROFILES

#### 3.1 Hα profile analysis

Normally, chromospheric emission fills the Hα profile in AB Dor, almost exactly to the level of the adjacent continuum (Collier 1982; Vilhu et al. 1987; Collier Cameron & Robinson 1989a,b). To a good approximation we can thus
treat the background illuminating source for the clouds as a flat continuum in Hα. When a cloud passes between the stellar disc and the observer, it scatters chromospheric Hα photons out of the line-of-sight. There is little coupling between the thermal properties of the cloud and the radiation field. In Paper I we inferred from statistical equilibrium studies that the cloud source function consists solely of the stellar radiation field, diluted according to the distance of the cloud from the star. The contributions of recombination and stimulated emission to the Hα source function are negligible. Since most of the clouds are located approximately 3 R_\star from the star, the cloud source function should be at most 3 per cent of the intensity of the chromospheric background in Hα. For this reason we expect to see a ‘pedestal’ of weak emission coming from off-disc clouds. In Paper I we found that the amplitude of the pedestal emission in a time-averaged spectrum was greatest at ± 3R_\star sin i from line centre, and was at most 1 or 2 per cent of the stellar background spectrum in Hα. This agrees with our expectations, because the majority of the clouds are located just outside the corotation radius and the clouds near the inner edge of the distribution will have the greatest surface brightnesses. This observed upper limit of 1 or 2 per cent on the pedestal emission tells us that the total projected area of all the clouds in the system is probably between one and five times the projected surface area of the star. Since the average cloud cross-sectional area is roughly 20 per cent of the disc area, this suggests that at any time there are between five and 20 clouds of this size surrounding the star, and that they form preferentially close to the stellar equatorial plane. Note that while all the clouds should contribute to the pedestal emission, they need not all transit the stellar disc, especially if the line-of-sight does not lie in the stellar equatorial plane. The estimate above of five to 20 clouds in total is thus consistent with the average number of transients (6-10) observed per rotation cycle.

The radial temperature gradient in the layers of the stellar chromosphere where Hα and the Ca II and Mg II resonance line emission features are formed is small enough that we are justified in neglecting centre-to-limb variations in the emission line profiles for a lowest order analysis.

In this very simple situation the observed equivalent width W of the cloud absorption profile is just the average of the absorption equivalent width w calculated along all lines-of-sight intersecting the stellar disc. Since the clouds appear to be well-defined, sharp-edged entities, we can also express the observed equivalent width in terms of the effective fraction of the stellar disc covered by clouds, and an area-weighted mean absorption equivalent width \( \tilde{w} \):

\[
W = \frac{1}{\pi R_\star^2} \int_\text{disc} w(x, y) \, dy \, dx
\]

\[
= \tilde{w} \frac{A_{\text{cloud}}}{A_\star}.
\]

If we can determine the value of \( \tilde{w} \) from the line profiles, we can use the observed equivalent width (EW) variations in Hα to determine the fraction of the stellar disc covered by clouds at any time.

In interpreting the shapes of the line profiles, we make the simplifying assumptions that:

(i) the cloud source function is zero;
(ii) the background continuum intensity \( I_0 \) is independent of wavelength across the width of the line;
(iii) the absorption equivalent width w is the same along all lines-of-sight intersecting a cloud and the stellar disc; and
(iv) there is no centre-to-limb variation in the chromospheric Hα surface brightness.

When no cloud is obscuring the disc, the observed continuum flux is

\[
F_c = I_0 \int_{-1}^{1} c(x) \, dx = \pi I_0.
\]

Here we define the independent variable x as the radial velocity along a given line-of-sight in units of \( v_\star \sin i \), or equivalently as the projected x-coordinate of the line-of-sight on the stellar disc in units of the stellar radius. A chord across the stellar disc, running through \( x \) parallel to the projected rotation axis, has a length \( c(x) = 2(1 - x^2)^{1/2} \). We also define a function \( h(x) \) to describe the shape of a section of the star obscured by cloud. The units of \( h(x) \) are the same as those of \( c(x) \), so that

\[
\int_{-1}^{1} h(x) \, dx = \pi \frac{A_{\text{cloud}}}{A_\star}.
\]

The rotation profile of the star is thus given by \( c(x) \), and the rotation profile of the part of the stellar disc occupied by clouds is given by \( h(x) \).

The observed line profile is the convolution of the background spectrum \( I(x) = I_0 \) with the rotation profile of the unobscured part of the disc, plus the convolution of the absorption profile \( I_c(x) \) along a single line-of-sight through the cloud with the cloud rotation profile:

\[
F(x) = I_0 \int_{-1}^{1} [c(x') - h(x')] \, dx' + \int_{-1}^{1} I_c(x - x') \, h(x') \, dx'.
\]

We obtain the fractional depression of the observed monochromatic flux below the level of the continuum from equations (6) and (8):

\[
\frac{F_c - F(x)}{F_c} = \frac{1}{\pi I_0} \int_{-1}^{1} \left[ I_0 - I_c(x - x') \right] h(x') \, dx'.
\]

In the limit where the cloud has a small extent in \( x \), giving a rotation profile \( h(x) \) narrower than the width of the intrinsic absorption profile \( I_c(x) \), we can treat \( h(x) \) as a delta-function with area \( \pi A_{\text{cloud}}/A_\star \), located at the \( x \)-coordinate \( x_c \) of the cloud centre. Equation (9) then simplifies to

\[
\frac{F_c - F_c}{F_c} = \frac{A_{\text{cloud}}}{A_\star} \left[ \frac{I_0 - I_c(x - x_c)}{I_0} \right].
\]

If the cloud absorption profile is saturated, then \( I_c(0) = 0 \). Provided that the instrumental resolution is sufficient to resolve the cloud profile, the fractional depression of the deepest part of the observed line profile is then equal to the fraction of the stellar disc obscured by the cloud. Note that if we integrate over \( x \), we recover the result of equation (5),
Masses of coronal clouds in AB Dor 421

In practice, this condition is satisfied for a time as the leading edge of a cloud starts to move on to the disc, and again as its trailing edge moves off the disc. During these opening and closing stages of a transient, the equivalent width of the observed profile is $W = \omega A_{\text{cloud}}/A_*$, and the fractional depth of the centre of the absorption profile is $[1 - F(x_i)/F_c] = A_{\text{cloud}}/A_*$. That is, a plot of the equivalent width against the depth of the observed absorption profile should give a straight line with slope $\omega$.

Figure 2. Hα absorption equivalent width plotted against central absorption depth. A total of 12 width–depth relations for individual clouds are shown, measured from the dynamic spectra of (a) 1988 December 16, (b) December 17, (c) December 19, (d) December 21 and (e) December 23. The slope of each plot gives the average Hα absorption equivalent width $\omega$ for a single line-of-sight through the cloud.
The cores of the Ca \(n\) \(H\) and \(K\) resonance lines in AB Dor show strong chromospheric emission reversals, giving a plentiful background source of photons in these lines. The effect of the circumstellar clouds on the observed profiles is similar to that in H\(\alpha\): Ca \(n\) \(H\) and \(K\) photons are scattered out of the line-of-sight when clouds pass between the stellar disc and the observer, giving rise to travelling absorption features in the dynamic spectra. No strong off-disc emission features are present in the dynamic spectra, indicating that once again the cloud source function in these lines is small, consisting mainly of scattered stellar Ca \(n\) \(H\) and \(K\) photons.

In interpreting the shapes of the Ca \(n\) \(H\) and \(K\) profiles, we make simplifying assumptions similar to those used in the discussion of the H\(\alpha\) profiles:

(i) the cloud source function is zero;
(ii) the total cloud column density is the same along all lines-of-sight intersecting a cloud and the stellar disc; and
(iii) there is no centre-to-limb variation in the chromospheric Ca \(n\) \(H\) and \(K\) spectrum.

If the underlying spectrum in the corotating frame is \(I_0(x)\), then the emergent spectrum along a line-of-sight through the cloud is

\[ I(x) = I_0(x) e^{-\tau(x)}. \]  

The observed monochromatic flux is obtained by convolving the underlying spectrum with the rotation profile of the unobscured part of the disc, and the absorbed spectrum with the rotation profile of the obscured part:

\[ F(x) = \int_{-1}^{1} I_0(x-x') [c(x') - h(x')] dx' + \int_{-1}^{1} I_0(x-x') h(x') dx'. \]

The total flux scattered out of the line-of-sight by the clouds is most conveniently expressed as a line index \(I_K\) or \(I_H\) measured relative to the total (unobscured) flux over a wavelength band extending from 1.5\(\nu\), sin \(i\) blueward to 1.5\(\nu\), sin \(i\) redward of line centre:

\[ I_{K,H} = \frac{\int_{-3/2}^{3/2} [F_0(x') - F(x')] dx'}{\int_{-3/2}^{3/2} F_0(x') dx'}. \]

If we define a similar line index for a single line-of-sight through the cloud

\[ i_{K,H} = \frac{\int_{-3/2}^{3/2} \{I_0(x') - I_0(x)\} dx'}{\int_{-3/2}^{3/2} I_0(x') dx'}, \]

we can see that to a good approximation, \(I_{K,H} = i_{K,H} A_{\text{cloud}}/A_{\ast}\), as is the case with the H\(\alpha\) equivalent widths. A plot of the observed line index \(I_K\) or \(I_H\) against H\(\alpha\) equivalent width \(W\) should give a straight line with slope \(i/\bar{w}\). This gives us a measure of \(\bar{w}\), since we can determine \(\bar{w}\) directly from the H\(\alpha\) profile width/depth variations:

\[ i_{K,H} = \frac{dK,H}{dW}. \]

In practice, this technique works best when we use short sequences of interleaved H\(\alpha\) and Ca \(n\) \(H\) and \(K\) observations.
made at times when the total amount of cloud coverage on the stellar disc is changing rapidly. Over longer periods, rotational changes in the background chromospheric emission flux can give rise to spurious drifts in the Hα equivalent width and the Ca II H and K line indices.

For shorter sequences, the dominant source of error in measuring the line core fluxes in the calibrated, normalized spectra lies in the polynomial fit used to straighten the continuum. We compensate for this by measuring the line core flux relative to two reference bands, each 0.75υ sin i wide, immediately adjacent to the line core band. Photon shot noise and readout noise then provide a good estimate of the uncertainty in each Une index measurement. For the December 19 and 23 data, we interpolate linearly in time to obtain the value of W at the time of each Ca II observation. For the continuous series of Ca II spectra taken on 1988 December 22, we can estimate the values of W at a given rotation phase by interpolation, using Hα spectra taken at the same rotation phase on 1988 December 21 and 1988 December 23. Fig. 3 shows the difference between values of W measured on these two nights, at the phase corresponding to a given ut on 1988 December 22.

In Fig. 4 we show the Ca II H and K line index–Hα equivalent width relation for a total of eight sequences on December 19, 22 and 23. The slopes of the straight-line fits to these plots are listed in Table 5. During the intervals used in Fig. 4 and Table 5, it can be seen that the phase-dependent changes in W did not evolve significantly between December 21 and 23. Note, however, that the time-dependent zero-point drifts in the I, K–W relations for December 22 are considerably greater than those on December 19 and 23. The Hα equivalent widths obtained using this technique may not be as reliable as those obtained by alternating observations at the two different wavelengths.

### Table 5. Observed Ca II H and K index–Hα EW relations.

<table>
<thead>
<tr>
<th>Date</th>
<th>UT Start</th>
<th>UT End</th>
<th>Échelle</th>
<th>dI, dW</th>
<th>dI, dW</th>
</tr>
</thead>
<tbody>
<tr>
<td>1988 Dec 19</td>
<td>14:41</td>
<td>16:19</td>
<td>143</td>
<td>—</td>
<td>0.125 ± 0.027</td>
</tr>
<tr>
<td>1988 Dec 19</td>
<td>14:41</td>
<td>16:19</td>
<td>144</td>
<td>0.188 ± 0.037</td>
<td>—</td>
</tr>
<tr>
<td>1988 Dec 19</td>
<td>16:39</td>
<td>17:42</td>
<td>143</td>
<td>—</td>
<td>0.071 ± 0.025</td>
</tr>
<tr>
<td>1988 Dec 19</td>
<td>16:39</td>
<td>17:42</td>
<td>144</td>
<td>0.261 ± 0.071</td>
<td>—</td>
</tr>
<tr>
<td>1988 Dec 22</td>
<td>04:12</td>
<td>04:53</td>
<td>087</td>
<td>0.299 ± 0.022</td>
<td>0.171 ± 0.014</td>
</tr>
<tr>
<td>1988 Dec 22</td>
<td>04:12</td>
<td>04:53</td>
<td>088</td>
<td>0.256 ± 0.020</td>
<td>—</td>
</tr>
<tr>
<td>1988 Dec 22</td>
<td>05:28</td>
<td>06:03</td>
<td>087</td>
<td>0.152 ± 0.021</td>
<td>0.071 ± 0.013</td>
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<tr>
<td>1988 Dec 22</td>
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<td>06:03</td>
<td>088</td>
<td>0.171 ± 0.019</td>
<td>—</td>
</tr>
<tr>
<td>1988 Dec 22</td>
<td>07:16</td>
<td>07:45</td>
<td>087</td>
<td>0.300 ± 0.022</td>
<td>0.207 ± 0.020</td>
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<tr>
<td>1988 Dec 22</td>
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<td>07:45</td>
<td>088</td>
<td>0.030 ± 0.029</td>
<td>—</td>
</tr>
<tr>
<td>1988 Dec 23</td>
<td>04:47</td>
<td>05:49</td>
<td>143</td>
<td>—</td>
<td>0.061 ± 0.013</td>
</tr>
<tr>
<td>1988 Dec 23</td>
<td>04:47</td>
<td>05:49</td>
<td>144</td>
<td>0.083 ± 0.016</td>
<td>—</td>
</tr>
<tr>
<td>1988 Dec 23</td>
<td>04:47</td>
<td>05:49</td>
<td>145</td>
<td>0.044 ± 0.023</td>
<td>—</td>
</tr>
<tr>
<td>1988 Dec 23</td>
<td>06:01</td>
<td>06:52</td>
<td>143</td>
<td>—</td>
<td>0.027 ± 0.011</td>
</tr>
<tr>
<td>1988 Dec 23</td>
<td>06:01</td>
<td>06:52</td>
<td>144</td>
<td>0.119 ± 0.014</td>
<td>—</td>
</tr>
<tr>
<td>1988 Dec 23</td>
<td>06:01</td>
<td>06:52</td>
<td>145</td>
<td>0.049 ± 0.020</td>
<td>—</td>
</tr>
<tr>
<td>1988 Dec 23</td>
<td>07:17</td>
<td>07:54</td>
<td>143</td>
<td>—</td>
<td>-0.009 ± 0.021</td>
</tr>
<tr>
<td>1988 Dec 23</td>
<td>07:17</td>
<td>07:54</td>
<td>144</td>
<td>0.025 ± 0.027</td>
<td>—</td>
</tr>
<tr>
<td>1988 Dec 23</td>
<td>07:17</td>
<td>07:54</td>
<td>145</td>
<td>0.050 ± 0.037</td>
<td>—</td>
</tr>
</tbody>
</table>

### 3.3 Mg II profile analysis

The analysis of the Mg II h and k profile variations on 1988 December 17 and 19 is very similar to that described above for the Ca II H and K data. Like the calcium, most of the magnesium in the clouds will be singly ionized and in the ground state. The chromospheric Mg II h and k emission provides a background source of photons which are scattered out of the line-of-sight by the clouds. Again the line source function in the clouds is expected to consist solely of scattering terms. The low level of the surrounding continuum allows us to place further constraints on the total projected surface area of the cloud system. The base widths of the Mg II profile are close to 3 Å. Clouds located just outside the corotation radius should produce pedestal emission between 2.0 and 2.5 Å to either side of line centre when they are near maximum elongation. The pedestal emission comprises no more than 30 per cent of the signal at this distance from line centre, and may be less because of the extended wings of the chromospheric emission features. If, as we argue below, the cloud optical thickness is such that the width of the absorption profile is similar to the emission base width, then the total scattered flux from the whole cloud system should be some 3 per cent of the total chromospheric emission flux multiplied by the total projected area of the cloud system in units of the stellar disc area. The upper limit
on the total scattered flux is of order $4 \times 10^{-13}$ erg cm$^2$ s$^{-1}$, while the total chromospheric emission flux is of order $4 \times 10^{-12}$ erg cm$^2$ s$^{-1}$. This implies a total projected area for the cloud system of three times the stellar disc area, in good agreement with the value inferred from the H$\alpha$ pedestal emission.

The procedures for forming line indices and calculating their dependence on cloud column density are nearly iden-
tical to those described above for Ca II, and so will not be repeated here. The band over which the line indices $I_{k,h}$ and $I_{k,h}^i$ are calculated extends from $2.0\nu_0 \sin i$ blueward to $2.0\nu_0 \sin i$ redward of line centre. No photospheric reference sidebands are used in this case because of the very low level of the surrounding continuum. The sensitivity of the LWP camera is sufficiently stable that the use of such sidebands is unnecessary. The line profiles and integrated fluxes have, however, been corrected for the effects of interstellar absorption as described in Section 2.6 above.

The main problem in interpreting the simultaneous Hα and Mg ii h and k data is the long exposure times of the IUE spectra. Substantial changes in cloud covering fraction often occurred during the Mg ii exposures, as seen from the changes in the Hα EW during each exposure. A second problem is that it was not possible to measure the intrinsic Hα EW ($\bar{w}$) for every cloud contributing to the Mg ii line index–Hα absorption EW relations.

The best we can do is to average all measurements of the Hα absorption equivalent width made during each Mg ii exposure, to obtain the time-averaged value of $W$ during the IUE exposure. Secondly, we must assume an average value of $\bar{w}$ in order to estimate the average cloud covering fraction during the exposure from the average value of $W$. We must bear in mind that the results may be affected by spurious zero-point drifts, caused by rotationally dependent changes in either the underlying Hα or Mg ii emission flux. However, the Hα width–depth plots for five different transients observed on 1988 December 17 and 19 all lie on the same relation (Fig. 2). This suggests that any such drifts are small, in Hα at least.

The observed Mg ii h and k line indices $I_{k,h}$ and the corresponding time-averaged $W$ values for the Hα absorption are listed in Table 6. The $I_{k,h}$–Hα absorption EW relations are shown in Fig. 5. The discrepant point in both these plots corresponds to the first IUE exposure made on 1988 December 19, LWP14672. Closer examination of this spectrum revealed that both the Mg ii emission and the surrounding continuum fluxes are consistently lower than the other exposures, by nearly a factor of 2. The reason for this flux deficiency is not clear: it is possible that the star was not properly centred in the entrance aperture.

If the data from LWP14672 are excluded, the $I_{k,h}$–Hα absorption EW relations are well-represented by linear relations, with slopes of $(dI_{k,h}/dW) = 0.58 \pm 0.06$ and $(dI_{h,k}/dW) = 0.49 \pm 0.06$, respectively. If we assume that the cloud scatters all the chromospheric Mg ii photons out of any line-of-sight intersecting the cloud, this implies an upper limit on $\bar{w}$ of

Figure 4 – continued
Table 6. Simultaneous Mg II h and k index and Hα EW measures. Note that W is a time-averaged value, calculated over the duration of the corresponding IUE exposure.

<table>
<thead>
<tr>
<th>Date</th>
<th>UT Start</th>
<th>UT End</th>
<th>W (Å)</th>
<th>I_k</th>
<th>I_H</th>
</tr>
</thead>
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<tr>
<td>1988 Dec 17 09:51</td>
<td>10:26</td>
<td>0.20</td>
<td>0.00 ± 0.05</td>
<td>0.00 ± 0.03</td>
<td></td>
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<tr>
<td>1988 Dec 17 11:40</td>
<td>12:20</td>
<td>0.57</td>
<td>0.27 ± 0.04</td>
<td>0.29 ± 0.03</td>
<td></td>
</tr>
<tr>
<td>1988 Dec 17 12:50</td>
<td>13:30</td>
<td>0.52</td>
<td>0.20 ± 0.04</td>
<td>0.12 ± 0.03</td>
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<tr>
<td>1988 Dec 17 14:04</td>
<td>14:44</td>
<td>0.79</td>
<td>0.38 ± 0.04</td>
<td>0.35 ± 0.02</td>
<td></td>
</tr>
<tr>
<td>1988 Dec 17 16:00</td>
<td>16:40</td>
<td>0.49</td>
<td>0.13 ± 0.04</td>
<td>0.04 ± 0.03</td>
<td></td>
</tr>
<tr>
<td>1988 Dec 19 13:20</td>
<td>13:55</td>
<td>0.35</td>
<td>0.55 ± 0.04</td>
<td>0.53 ± 0.02</td>
<td></td>
</tr>
<tr>
<td>1988 Dec 19 14:29</td>
<td>15:04</td>
<td>0.22</td>
<td>0.13 ± 0.05</td>
<td>0.14 ± 0.03</td>
<td></td>
</tr>
<tr>
<td>1988 Dec 19 15:37</td>
<td>16:17</td>
<td>0.43</td>
<td>0.16 ± 0.05</td>
<td>0.21 ± 0.03</td>
<td></td>
</tr>
</tbody>
</table>

1.90 ± 0.15 Å. This is within the scatter of the distribution of $\bar{\mu}$ values measured from the Hα width-depth relations. This indicates that the width of the absorption profile of a typical cloud in the Mg II resonance lines is comparable with the base width of the chromospheric emission features, and so places a lower limit on the cloud optical thickness.

4 LINE INDEX-COLUMN DENSITY RELATIONS

4.1 Hα profile synthesis

For the larger clouds studied here, the range in intrinsic Hα absorption equivalent widths $\bar{\mu}$, and hence in column densities of hydrogen atoms in the first excited state ($n=2$), is small (Table 3). These larger clouds have projected surface areas between 13 and 18 per cent of the stellar disc area, so it is not too surprising that their other physical properties should be fairly similar.

The equivalent width of the Hα absorption profile depends principally on:

(i) the total column density of cloud material;
(ii) the degree of excitation and ionization of hydrogen in the cloud interior; and
(iii) the amplitude of turbulent random motions within the cloud.

Turbulent motions within the cloud have the effect of broadening the Doppler core of the absorption profile, although this is less important for hydrogen than for heavier atoms with small Doppler widths. By analogy with quiescent solar prominences, we suspect that turbulent motions may be important in the AB Dor clouds. The clouds are likely to have a highly fragmented structure: the effective pressure scaleheight in the cool cloud material is determined by the combined gravitational acceleration and the cloud temperature, and is of order 200–300 km, which is very much smaller than the overall cloud extent. Nakagawa & Malville (1969) found that in the solar case, the prominence-corona interface was unstable to fragmentation for perturbations with wavelengths longer than the pressure scaleheight. Given that conditions inside the AB Dor clouds are likely to be similar, it seems plausible that filamentary structures similar to those seen in quiescent solar prominences may be present, and that individual elements of this fine structure may have random velocities at least as great as the 5–10 km s$^{-1}$ observed by Engvold (1972) in the solar case.

In Fig. 6 we show contours of constant Hα absorption equivalent width $\bar{\mu}$, computed as a function of the column density of H atoms in the $n=2$ level and a Gaussian turbulent velocity component. The contours span the observed range of $\bar{\mu}$ values, and show little change as the turbulent velocity dispersion is increased from 0 to 20 km s$^{-1}$. The range in column density of singly excited H atoms permitted by the observations spans less than an order of magnitude: for a turbulent velocity of 10 km s$^{-1}$, log $n_{n=2} = 14.4 ± 0.2$ cm$^{-2}$.

The degree of excitation of hydrogen within the cloud is influenced mainly by the cloud kinetic temperature, and to a lesser extent by the volume density of the cloud material. The statistical equilibrium in the cloud interior was discussed in some detail in Paper I, to which the reader is referred for
Figure 6. Intrinsic Hα absorption EW as a function of $n_{\text{H},2}$ and $v_{\text{turb}}$. The contours are drawn at levels of constant $\bar{\lambda} = 1.8, 2.2, 2.6$ and 3.0 Å.

Figure 7. Intrinsic Hα absorption EW as a function of $n_{\text{H},2} + n_{\text{p}}$ and $T_{\text{cloud}}$. The cloud thickness is $7.3 \times 10^{10}$ cm and the turbulent velocity dispersion is $v_{\text{turb}} = 10$ km s$^{-1}$. The contours are drawn at levels of constant $\bar{\lambda} = 1.8, 2.2, 2.6$ and 3.0 Å.

Further details. Here we use the same model with a 5-level H atom plus continuum, and the Lyman lines and continuum in radiative detailed balance. In Fig. 7 we show contours of constant $w$ as a function of cloud temperature and total hydrogen column density $n_{\text{H},2} + n_{\text{p}}$, computed using a turbulent Gaussian velocity dispersion of 10 km s$^{-1}$.

Fig. 7 was computed for a slab of uniform density with a thickness of one stellar radius, comparable to the projected linear dimensions of the clouds. If the clouds are significantly fragmented, however, the local density in the neutral material will be very much greater than we have assumed. We can explore this possibility by computing a second set of models in which the slab thickness is decreased by a factor of 1000 and the local density increased by the same factor to give the same total column density. The results are shown in Fig. 8. At temperatures below 8000 K there is little difference.
between the uniform and fragmented models. At higher temperatures, however, when a substantial fraction of the hydrogen is ionized, the higher local densities in the fragmented model serve to increase the recombination rate, increasing the amount of neutral hydrogen relative to the uniform density model. The observed optical thickness in Hα is thus achieved at a column density up to an order of magnitude lower in the fragmented model than in the uniform model.

Figs 7 and 8 show clearly that the observed Hα equivalent widths effectively rule out total cloud column densities less than \((8 \pm 4) \times 10^{18}\) cm\(^{-2}\). This lower limit on the column density occurs at a temperature close to \(1.1 \times 10^4\) K, where the number density ratio of H atoms in the \(n = 2\) level passes through a maximum relative to the total number density \((n_H + n_F)\). At higher temperatures, the increasing degree of excitation is offset by the decrease in the amount of neutral hydrogen as the hydrogen becomes ionized; while at lower temperatures the hydrogen is mainly neutral but the degree of excitation is lower.

4.2 Ca ii profile synthesis

We now need to calibrate the variation of \(I_{K, H}\) with column density. The amount of flux scattered out of a single line-of-sight depends on:

(i) the width of the chromospheric emission core in the background stellar spectrum as seen in the corotating frame of the cloud;

(ii) the velocity dispersion of the Ca ii ions in the cloud; and

(iii) the column density of Ca ii ions in the cloud.

Although we cannot determine the intrinsic width of the emission core directly (owing to the extreme rotational broadening of the spectrum) we can make a reasonable estimate based on observations of more slowly rotating, active stars of similar spectral type. Empirical studies of Ca ii H and K emission profile widths in a large number of dwarfs and giants with a range of spectral types and chromospheric activity levels show that the full widths at half maximum (FWHM) of the chromospheric Ca ii emission cores are insensitive to the level of chromospheric heating, although they are very sensitive to surface gravity (Wilson & Bappu 1957). In a theoretical study of chromospheric scaling laws, Ayres (1979) found that the base width \(\Delta \lambda_0\) of the chromospheric Ca ii emission cores and the thermalization width \(\Delta \lambda_\alpha\) have equal and opposite dependences on metallicity, stellar effective temperature and chromospheric heating, but the same dependence on surface gravity. The thermalization width corresponds to the separation of the red and blue peaks of the emission profile. The functional dependence of the FWHM of the emission profile on the various stellar parameters is intermediate between those of the base width and the thermalization width: that is, the effects of metallicity, effective temperature and chromospheric heating cancel out, leaving only the gravity dependence of the Wilson–Bappu effect.

The compilation of high-resolution Ca ii H and K profiles of late-type stars by Linsky et al. (1979) gives FWHM values for several stars of similar surface gravity and spectral type to AB Dor. The scatter in these widths is small, and we adopt a mean value of \(0.43 \pm 0.04\) Å as the FWHM of the Ca ii H and K emission cores in AB Dor. For modelling purposes, we represent the background spectrum by a Gaussian emission core of appropriate width and amplitude, superimposed...
on a parabolic fit to the broad photospheric absorption profile.

The atomic parameters used in calculating the line absorption profiles are listed in Table 4. The thermal Doppler width of the absorption profile is $1.2 \pm 0.2$ km s$^{-1}$ over the temperature range 5000–10 000 K, in which the cloud temperature is expected to lie. As described above, however, we also consider the possibility that turbulent broadening of up to 20 km s$^{-1}$ may also be present due to random motions of fragmented substructures within the clouds.

In Fig. 9 we plot contours of constant line index $i_K$ and $i_H$ as a function of cloud column density and turbulent velocity, for an assumed cloud temperature of 8500 K and a background emission core width of 0.43 Å. The effects of varying the background emission core width are illustrated in Fig. 10: the effects on the line index are negligible.
Figure 10. Ca ii H and K line index plotted against total hydrogen column density. The solid curve shows the variation of the line index with column density, for zero turbulent velocity dispersion and a Gaussian chromospheric emission profile with FWHM = 0.43 Å. The effects of increasing or decreasing the chromospheric emission width by ±0.04 Å are shown by the dashed and dotted curves, respectively. The effect of introducing a turbulent Gaussian velocity dispersion of 4 km s^{-1} is shown by the dot-dashed curve.

We can use the model line index maps shown in Fig. 9 to determine a confidence region in (n_H + n_p, v_{turb}) space, within which we can achieve a satisfactory fit to the observations. For each sequence of n Ca ii observations of a single absorption transient, we usually had observations of the K-line in two different échelle orders, and of the H-line in a single order. Each (n_H + n_p, v_{turb}) pair defines the slope of a theoretical line index–Hα equivalent width relation, in each of the H and K lines. At each value of n_H + n_p and v_{turb} we fix the slope at the theoretical value, and determine the zero-point offset for each line in each order, by minimizing the statistic

\[ S = \sum_{i=1}^{n} \frac{D_i - F_i}{\sigma_i}, \]  

where D_i and F_i are the observed and predicted data values and \( \sigma_i \) is the observational scatter. We then sum the resulting values of S for all lines and orders, and so build up a map of S as a function of n_H + n_p and v_{turb}, incorporating all the data on each individual cloud observed.

We identify the contours of constant S corresponding to the 95.4 and 99.0 per cent confidence limits on (n_H + n_p, v_{turb}) using the parameter estimation method of Lampton, Margon & Bowyer (1976). The value S_t on the contour that has a probability \( \alpha \) of enclosing the true values of the parameters is given by

\[ S_t = S_{\text{min}} + \chi^2_{\alpha}(\alpha). \]  

Here S_{\text{min}} is the minimum value of S in the map, and \( \chi^2_{\alpha}(\alpha) \) is the tabulated value of the \( \chi^2 \) distribution for \( p \) degrees of freedom and significance \( \alpha \). In this case there are two free parameters, so that \( p = 2 \). The 95.4 and 99.0 per cent confidence regions in (n_H + n_p, v_{turb}) space are shown for the eight clouds observed, in Fig. 11.

We verified that \( p = 2 \) was the correct choice by Monte Carlo simulation, as follows. We assume that the ‘true’ cloud parameters are those giving the minimum value of S, i.e. \( S_{\text{true}} = S_{\text{min}} \). Using these parameters we generate a large number of artificial data sets with normally distributed errors. For each artificial data set we generate a new map of \( S(n_H + n_p, v_{turb}) \), and locate the minimum value \( S_{\text{min}} \). The value of S corresponding to this \( (n_H + n_p, v_{turb}) \) pair in the original map derived from the actual data is noted. After \( n \) such simulations, we sort the \( n \) resulting S values into ascending order, and note the limiting values \( S_t \) below which 95.4 and 99.0 per cent of the simulated minima lie. We found good agreement between the contour levels estimated in this way and those estimated by the method of Lampton et al. (1976).

4.3 Mg ii profile synthesis

The modelling of the Mg ii line profiles as viewed in the co-rotating frame (and hence the Mg ii line indices \( i_{H\alpha} \)) as functions of the cloud column density was very similar to that used for the Ca ii profiles. Again the chromospheric emission profile was approximated by a Gaussian. The width of the synthetic profile was based on IUE observations of chromospheric Mg ii emission profile widths for several nearby late-G and early-K dwarfs (Basri & Linsky 1979). As with the Ca ii profiles of Linsky et al. (1979), the scatter in the profile widths for the stars in the Basri & Linsky sample is small, and we adopt a mean FWHM of 0.60 ± 0.06 Å for our synthetic Gaussian profile.

Fig. 12 shows contours of constant line index \( i_H \) and \( i_K \) as functions of cloud column density and turbulent velocity, for an assumed cloud temperature of 8500 K and a background emission core width of 0.60 Å. In Fig. 13, the effects on the line index–column density relations of varying the background emission core width by ±0.06 Å are represented as in Fig. 10: once again, the line index is seen to be insensitive to errors in the estimated width of the chromospheric emission core.

The contours of constant \( \chi^2 \) bounding the 95.4 and 99.0 per cent confidence regions in (n_H + n_p, v_{turb}) space, within which we can obtain a satisfactory fit to the combined 1988
December 17 and 19 Mg \( \Pi \) \( h \) and \( k \) line index–H\( \alpha \) EW relations, excluding LWP14672, are shown in Fig. 14.

5 CLOUD MASSES AND INTERNAL VELOCITY FIELDS

Using the techniques developed in Section 3 we have succeeded in measuring both the equivalent width of the H\( \alpha \) absorption and the amount of the Mg \( \Pi \) and Ca \( \Pi \) resonance line scattering, along typical lines-of-sight running through some of the larger circumstellar clouds. When compared with the line profile synthesis results of Section 4, the observed line indices provide a set of independent constraints on the column densities, temperatures and turbulent internal velocity dispersions of the clouds. The H\( \alpha \) equivalent widths are more sensitive to the density and tempera-
ture of the cloud material than to the random internal motions. The Ca II H and K and Mg II h and k line indices are more sensitive to column density and turbulent motions than to cloud temperature.

The Hα equivalent widths of the various clouds studied show remarkably little scatter. If the physical conditions affecting the degree of excitation and ionization of hydrogen are similar for all the clouds, this would imply that the total hydrogen column density is similar for the various clouds studied. The situation for the Ca II resonance lines is not quite so simple. For a fixed turbulent velocity dispersion, the scatter in the inferred column density varies by as much as two orders of magnitude from cloud to cloud. The three clouds for which we obtained good Ca II line index–Hα equivalent width relations on 1988 December 22 and 23 showed a marked decrease in Ca II absorption over the course of two stellar rotations. Over the same period, however, the Hα equivalent width and fractional area coverages underwent only minor evolution.

There are two possible explanations for this behaviour.
First, the amount of material in each of these three physically distinct clouds may have decreased by a factor of between 10 and 100 between 1988 December 22 and 23. Let us suppose that the clouds are in thermal equilibrium, such that a fixed rate of conductive and mechanical energy input is balanced by radiative losses in strong, effectively thin lines such as the hydrogen Balmer series and the MgII and CaII resonance lines. In this case, a drop in the cloud density will lead to an increase in temperature until the electron density (and hence the radiative loss rate) has attained more or less its original value. At the temperatures and densities considered here, the $n=2$ level population of hydrogen varies almost in direct proportion to the electron density, provided that the degree of ionization of the cloud material is small. This 'thermostat' acts to keep the Hα absorption equivalent width at a nearly constant value. At temperatures above $10^4$ K, however, hydrogen is almost completely ionized so that this mechanism breaks down. As Figs 7 and 8 show, the lowest total column density that can possibly give rise to the observed Hα equivalent widths is of order $10^{19}$ cm$^{-2}$, so that the total...
column densities on 1988 December 22 must have been one to two orders of magnitude greater, i.e. at least $10^{20}-10^{22}$ cm$^{-2}$.

The second possibility is that the column density and temperature did not change. Instead, the decrease in the strength of the Ca\II absorption could have been caused by a change in the average amplitude of the turbulent motions inside the clouds, from 10–20 km s$^{-1}$ on December 22 to 4 km s$^{-1}$ or less on December 23. The solar analogy provides some evidence in favour of this idea. Solar quiescent prominences often undergo temporary increases in the amplitude of their internal motions. These activations usually occur in response to a solar flare, when large-scale magnetic wave disturbances spread out through the corona, propagating large distances over the surface of the Sun at speeds of order 1000 km s$^{-1}$. The internal motions in the prominence increase from the usual 5–10 to 30–50 km s$^{-1}$, and after an hour or so may either die down or lead to an outward eruption of the
Contour lines of constant Mg II k index $i_k$

Figure 12. Mg II $h$ and $k$ absorption line index map. Contours of constant (a) $i_k$ and (b) $i_h$ are plotted as a function of total hydrogen column density $n_H + n_\text{e}$ and turbulent velocity dispersion $v_{\text{turb}}$. From bottom to top, contour levels are 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9.

entire prominence (Bruzek 1969). Given that AB Dor undergoes strong soft X-ray flares at a rate of one or two per day (Pakull 1981; Vilhu & Linsky 1987; Collier Cameron et al. 1988), this explanation seems plausible and has the added attraction that it can explain why three physically distinct circumstellar clouds should all show enhanced Ca II absorption only during one 4-hr series of observations, on December 22. Further simultaneous optical and X-ray observations are planned for the near future, and should allow us to determine whether X-ray flares and Ca II absorption enhancements are correlated.

In Table 7 we list the various constraints on the cloud temperature and internal motions, as functions of column density. The range of cloud temperatures consistent with the observed Hα equivalent width is listed, for a cloud model with uniform density (filling factor $f = 1$, as in Fig. 7) and for
each of the clouds observed in Ca II H and K (Fig. 11). Under the assumption that the differences in Ca II absorption from cloud to cloud are due to differences in internal velocity dispersion rather than column density, it seems that the only value of the column density that is capable of satisfying all the observational constraints simultaneously, is $n_H + n_p = 10^{20}$. The corresponding cloud temperature needed to give the observed Hα equivalent width lies in the range 8000–9000 K, and the internal motions of the clouds range from less than 2 km s$^{-1}$ to more than 14 km s$^{-1}$.

The cross-sectional areas of all the clouds studied in Ca II H and K and Hα were in the range 0.15–0.20 times the projected area of the stellar disc. For a column density of $10^{20}$ cm$^{-2}$, this gives a mass of 4 to $5 \times 10^{17}$ g per cloud. The amount of energy needed to increase the turbulent velocity dispersion of such a cloud from ~5 to ~15 km s$^{-1}$ is of order $5 \times 10^{32}$ erg—a small fraction of the $\sim 10^{34}$ erg released in 0.1–10 keV X-rays by a single large flare on AB Dor (Collier Cameron et al. 1988).

The energy budget for disposing of between 90 and 99 per cent of the material in three clouds between 1988 December 22 and 23 is considerably greater. A large fraction of the cool cloud material seen on 1988 December 22 material must either have been re-ionized, fallen back to the surface of the star or been ejected from the corona by December 23. The amount of energy needed to re-heat most of the material in a $4 \times 10^{17}$ g cloud to the ambient coronal temperature of $2 \times 10^7$ K is of order $10^{33}$ erg. Alternatively, the confining field may have contracted, dragging the cloud down to a position inside the corotation radius, where the dense cloud material is free to drain back on to the chromosphere, releasing $10^{32}–10^{33}$ erg of gravitational energy per cloud as it goes. A third possibility is that part of each cloud may have undergone centrifugal ejection from the confining field, again releasing at least $10^{33}$ erg of magnetic energy from the stressed magnetic configuration. However, the apparent stability of the radial positions and projected areas of these three clouds, and the lack of any obvious bulk motions (absorption blueshifts or redshifts) during the period 1988 December 21 to 23, tends to argue against any hypothesis requiring all three clouds to shed most of their contents in such a spectacular fashion in the course of 24 hr.

6 CONCLUSIONS

The new techniques developed in this paper for measuring the strength of the Hα, Ca II H and K and Mg II h and k absorption along lines-of-sight intersecting a cool circum-

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Table 7. Constraints on cloud temperature and velocity dispersion.

<table>
<thead>
<tr>
<th>$n_H + n_p$</th>
<th>$T_{\text{cloud}}$ (f = 1.000)</th>
<th>$T_{\text{cloud}}$ (f = 0.001)</th>
<th>Mg II h &amp; k</th>
<th>Ca II H &amp; K</th>
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</thead>
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<tr>
<td>$10^{22}$</td>
<td>$6000 \pm 200$</td>
<td>$6000 \pm 200$</td>
<td>Unc.</td>
<td>Excl.</td>
</tr>
<tr>
<td>$10^{21}$</td>
<td>$7000 \pm 300$</td>
<td>$7000 \pm 300$</td>
<td>Unc.</td>
<td>&lt; 3</td>
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<tr>
<td>$10^{20}$</td>
<td>$9000 \pm 1000$</td>
<td>$8200 \pm 400$</td>
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<td>2-10</td>
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<tr>
<td>$10^{19}$</td>
<td>Excl.</td>
<td>$12000 \pm 2000$</td>
<td>&gt; 10</td>
<td>Excl.</td>
</tr>
<tr>
<td>$10^{18}$</td>
<td>Excl.</td>
<td>Excl.</td>
<td>&gt; 15</td>
<td>Excl.</td>
</tr>
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</table>

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stellar cloud have been applied successfully to new optical and UV spectra of AB Dor. These measurements place important new constraints on the masses and internal velocity dispersions of the AB Dor cloud system. The average amount of Hα absorption along lines-of-sight through several of the larger clouds shows little variation, either from night to night or from cloud to cloud. The Ca n H and K absorption, however, can change dramatically from night to night in a given cloud. These changes correspond to changes of one or two orders of magnitude in the cloud column density at a fixed internal velocity dispersion. A more plausible explanation for these changes in the Ca n H and K absorption is that the internal velocity dispersions of the clouds may vary in time over the range 5–20 km s⁻¹—possibly increasing in response to stellar flares—in a manner analogous to the activation of solar prominences. In this case, a column density $n_H + n_e = 10^{20}$ cm⁻² is consistent with all the observations. The projected cross-sectional areas of these clouds are 15–20 per cent of the projected stellar disc area, giving total masses per cloud of $2–6 \times 10^{17}$ g.

The excitation temperature for hydrogen needed to match the observed Hα EW is between 8000 and 9000 K. If we take into account the combined local gravitational and centrifugal acceleration, the pressure scaleheight in the clouds is thus a few hundred kilometres. By analogy with solar quiescent prominences, where similar physical conditions prevail, we suspect that the cloud material may be concentrated in filamentary structures with local densities two to three orders of magnitude greater than the average cloud density. The amplitude of the turbulent velocity dispersion inferred from the Ca n H and K absorption strength is similar to the amplitude of the random motions of filaments within quiescent solar prominences.

At any given time there appear to be of order 6–10 large clouds in the observable slice of the corona, with allowance made for incomplete phase coverage. The actual number of clouds is probably at least twice this number, giving a total mass for the cloud system of order $10^{19}$ g.

ACKNOWLEDGMENTS

ACC thanks the director and staff of the Anglo–Australian Observatory, for support at the telescope and for the use of the VAX 11/780 computer at AAO Epping, where the early stages of the data reduction were carried out. BHF and PE thank the staff of the ESO for their support during the La Silla observations. MVP thanks the Institute of Astronomy, Cambridge for hospitality during the period over which this work was carried out, and the staff at Vilspa for support during the ESA IUE observations. DD, KK and DS thank the support staff of the IUE observatory at the Goddard Space Flight Center for their help in obtaining observations, particularly over the Christmas holiday period. We acknowledge the use of the software and data analysis facilities provided by the STARLINK Project, which is funded by the UK SERC: the later stages of the data analysis were performed on the STARLINK VAX 11/780 at the Royal Greenwich Observatory. One of us (DD) gratefully acknowledges the support of NASA IUE grant NAG 5-973. This research was also supported in part by a NASA grant to DS. During the course of this work ACC was supported in a SERC-funded postdoctoral fellowship at the University of Sussex. An EEC grant to BHF for research into stellar activity is also acknowledged.
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