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Simultaneous ORFEUS FUV and ROSAT X-ray observations of the young rapid rotator AB Doradus

Jürgen H.M.M. Schmitt[1], J. Krautter[2], I. Appenzeller[2], H. Mandel[2], R. Wichmann[2], J. Barnstedt[3], M. Gölz[3], M. Grewing[3], W. Gringel[3], C. Haas[3], W. Hopfensitz[3], N. Kappelmann[3], and G. Krämer[3]

[1] Max-Planck-Institut für Extraterrestrische Physik, Postfach 1603, D-85740 Garching, Germany
[2] Landessternwarte Königstuhl, D-69117 Heidelberg, Germany
[3] Institut für Astronomie und Astrophysik Tübingen, Germany

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Abstract. We present simultaneous soft X-ray and FUV observations of the rapidly rotating young star AB Doradus (HD 36705), obtained with the position sensitive proportional counter (PSPC) on board ROSAT and the FUV/EUV spectrometer on board ORFEUS. The X-ray data show that AB Dor was in a high state, possibly in a flare, during the FUV observations. The lines of CIII at 977 Å and OVI at 1032 and 1038 Å are clearly detected in the ORFEUS spectrum. The overall emission measure distribution of the combined FUV and X-ray data is steeply rising. The OVI 1032 Å line is definitely broadened with respect to the instrumental line profile, however, the observed broadening does not exceed the photospheric $vsin(i)$-value. This strongly suggests that the observed OVI emission, formed at a characteristic temperature of $\approx$ 300000 K, is produced almost exclusively relatively close to the star's surface, and not in an extended corotating emission region with scale sizes of a few stellar radii.

Key words: stars: coronae – stars: activity – stars: late-type – stars: rotation – stars: individual: AB Dor

1. Introduction

The Large Magellanic Cloud (LMC) foreground star AB Doradus (= HD 36705) has in recent years become one of the best studied cool stars. It is relatively bright optically ($m_v \sim 6.7$), and was "discovered" (as an astrophysically particularly interesting object) during a survey of the LMC with the *Einstein Observatory* IPC (cf., Pakull 1981) as a rather bright X-ray source: The X-ray output of AB Dor exceeds that of the Sun by more than a factor of 1000, yet the sizes of these two stars are quite similar. Extensive X-ray studies of AB Dor have been undertaken with EXOSAT (cf., Cameron *et al.* 1988) and ROSAT (cf., Kürster *et al.* 1997) and other satellites. Optically, AB Dor also exhibits unusual properties. It shows rather large amplitude photometric variations with a recurrence period of P = 0.514 days, which is identified with the rotation period of the star. This rapid rotation leads to an apparent $v\ sin(i)$ value of 95 km/sec, which is large enough to make AB Dor suitable for Doppler imaging. The first Doppler images of AB Dor have been obtained by Kürster *et al* 1994, and since then AB Dor has been Doppler-imaged at regular intervals. The Doppler images of AB Dor consistently show an arrangement of dark areas on the star in belt-like regions, sometimes a polar spot is visible (a feature that is of course never seen on the Sun). Clearly, both the photosphere and the corona of AB Dor have got to be quite different from their solar analogs. Obviously stars, which are rather similar with respect to mass and radius, can manage to produce vastly different X-ray outputs. There are basically two schools of thought on this issue: One group of researchers assumes that the coronal volume of closed magnetic structures is much larger than on the Sun and actually filled with hot plasma; since the coronal temperatures are high ($T_{cor} > 10^7$K), the scale height is large and can extend out to a few stellar radii. The other school of thought assumes that the coronal density is rather large; since the magnetic filling factor in the photospheres of active stars as deduced from Doppler images is large (30 percent or maybe more compared to 0.1 percent or less for the Sun), there is much less magnetic field expansion and hence reduction in magnetic field strength when going out from the photosphere into the corona. The coronal magnetic field strengths should therefore be larger and be able to confine higher density plasma.

With low spectral resolution data these two scenarios cannot be distinguished from one another since in the case of optically thin emission the observed total flux in some given line or band pass is proportional to the emission measure EM, i.e., the product of volume V and the square of density n. With high spectral resolution data, however, the two scenarios can be readily

Send offprint requests to: J.H.M.M. Schmitt (jhs@rosat.mpe-garching.mpg.de)

distinguished from the observed line profiles. Since magnetic structures are anchored in the stellar photospheres, they must rotate rigidly with the surface at least out to a few stellar radii. Thus the "large volume scenario" should lead to a much broader line profile than the case of the "high density scenario", which in turn should lead to a line width more or less consistent with measurements in the optical regime. Since AB Dor is rotating already with $v\ sini(i)$ = 95 km/sec at one stellar radius, one is definitely in the parameter regime where ORFEUS measurements can make new and valuable contributions.

Finally, AB Dor shows a possibly unique property among late-type active stars. Transient, rapidly moving absorption events are seen in H_α, CaII and MgII profiles (cf., Collier-Cameron *et al.* 1990; Collier-Cameron & Robinson 1989); these absorption events are interpreted as being caused by a system of prominence-like condensations of mostly neutral material, but nevertheless magnetically trapped at the corotation radius between 3 - 10 stellar radii. At any given time there appear to be around a dozen or so clouds in the system with a total mass approaching 10^{19} g. This material is hypothesized to form via thermal collapse from loops extending to beyond the corotation radius at a rate of 0.5 per day or so. After thermal collapse the material slowly leaves the system, thus contributing significantly to the total angular momentum loss. The relevance of the ORFEUS observations presented here lies in the fact that some temperature range of the cooling plasma is expected to emit in the FUV and hence in the ORFEUS band pass, and is therefore amenable to study with rather high and unprecedented spectral resolution.

The plan of our paper is as follows: In sect. 2 we describe our new simultaneous ROSAT and ORFEUS observations, in sect. 3 we describe the spectral analysis of the X-ray data and especially the FUV data, and in sect. 4 we present our conclusions specifically with respect to the asserted presence of cool magnetically confined material at large distances from the star's surface.

2. Observations and data analysis

We have obtained observations of AB Doradus taken simultaneously with the EUV/FUV spectrometer on board ORFEUS (**O**rbiting **R**etrievable **F**ar and **E**xtreme **U**ltraviolet **Sp**ectrometer), and the position sensitive proportional counter (PSPC) on board the ROSAT X-ray satellite. A detailed description of ROSAT and its scientific instruments has been given by Trümper (1983). ORFEUS is (like ROSAT) a joint DARA/NASA project, successfully flown aboard Astro-SPAS (Shuttle Pallet Satellite) in September 1993, and recaptured five days later by the Space Shuttle. During this flight more than hundred pointings at various celestial sources were carried out. Briefly, ORFEUS carries a normal incidence 1m telescope especially coated to provide reflectivity down to 500 Å. A high-resolution ($\lambda/\Delta\lambda \sim 3000$) spectrometer, utilizing gratings with variable line spacing, is located at the prime focus of the telescope and allows spectroscopy of the EUV and FUV band with reasonable sensitivity ($\approx$ 4 cm^2 effective collecting area). The

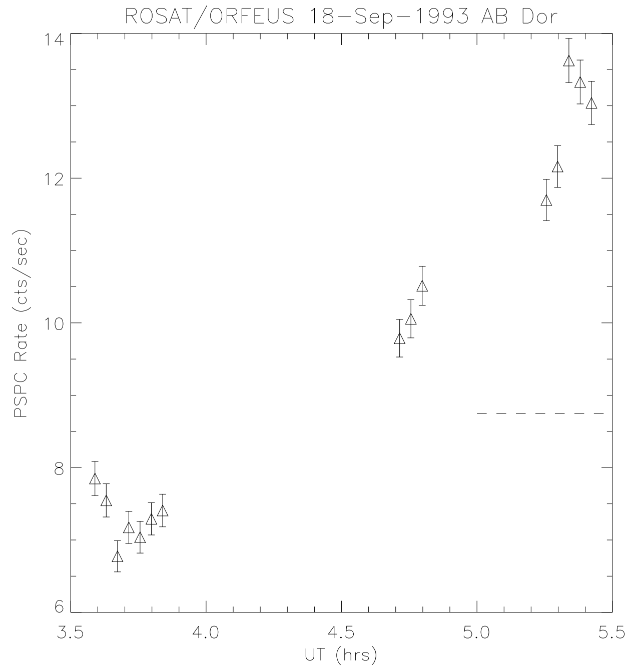

Fig. 1. ROSAT PSPC light curve of AB Dor during the observation on Sep 18, 1993. The simultaneous coverage of the ORFEUS spectrum is also indicated: see text for details.

diffracted photons are recorded with a MCP detector operating in photon counting mode. A more detailed description of the ORFEUS hardware has been presented by Grewing et al. (1991) and Hurwitz and Bowyer (1991).

2.1. ROSAT X-ray observations

AB Dor was observed with the ROSAT position sensitive proportional counter (PSPC) on Sep 18, 1993 between UT 3:30 and UT 5:30. The source was placed on axis, the useful scientific observing time was approximately 7000 seconds. The data were obtained in three different observation intervals, separated by about 45 minutes from each other. The last of these observation intervals coincided almost exactly with the ORFEUS observations described in the following subsection. The PSPC data for AB Dor were analyzed following standard procedures (cf., Zimmermann et al. 1994). In order to construct an X-ray light curve, we first extracted the source photons within an extraction radius of 2.5 arc minutes around the apparent position of AB Dor. Since the source is rather strong, we did not correct for background which constitutes less than 1 % of the overall signal. In Fig. 1 we show the dead time corrected PSPC light curve of the whole ROSAT observation; the interval with simultaneous ORFEUS coverage is also indicated.

Inspection of Fig. 1 reveals that a substantial flux increase in the form of possibly a flare has been in progress during the ORFEUS observations; during the whole span of ROSAT observations AB Dor's count rate was increasing from about 7 counts/sec to 13 counts/sec. We of course do not know AB Dor's peak count rate during this event, but comparing the data

Table 1. PSPC Spectral fit results

T_1 (keV)	log EM_1 (cm^{-3})	T_2 (keV)	log EM_2 (cm^{-3})	abundance w.r.t solar	χ^2_{red}
0.80	52.95	n.a.	n.a.	0.14	1.41
0.19	53.14	1.00	52.85	1.00	1.11

shown in Fig. 1 with the long-term monitoring data of AB Dor presented by Kürster *et al.* (1997), it appears likely that the peak count rate did not significantly exceed 15 cts/sec. Interestingly, no significant spectral changes in the PSPC pulse height spectra are observed during the count rate increase. This coupled with the fact that the increase in count rate lasted at least two hours suggests that one does not necessarily need to interpret this event as a flare, which often - albeit not always - have much shorter rise times. If one instead chooses to interpret the observed increase as caused by rotational modulation, one finds a rise time of almost two hours, i.e., one sixth of the rotation period, which would imply scale heights of the order of a stellar radius. In this case the count rate would be expected to remain high for a couple of hours beyond the ORFEUS observations. Alternatively, we can interpret the event as a rather intense coronal brightening, and obviously, from the available data we cannot decide which possibility to choose.

For the purposes of comparison between ORFEUS and PSPC, we extracted the PSPC data from only the last observation interval and carried out a spectral analysis of the pulse height data. In order to avoid modeling ambiguities we considered only simple spectral models; first, we considered a variable abundance single temperature model with interstellar absorption, i.e., with four fit parameters, and second a solar abundance two-temperature model again with interstellar absorption fixed at the single temperature value of $N_H = 1.7\,10^{19}\,cm^{-2}$. The derived parameters are summarized in Table 1; we emphasize that we consider these models merely as simple parametrisations and not necessarily as representing physically distinct components.

2.2. ORFEUS FUV observations

AB Dor was observed with the ORFEUS spectrometer on Sep 18, 1993, between 5:00 and 5:30 UT; the total accumulated integration time was 1794 seconds. The data were reduced in the same way as described by Raymond et al. (1995). The resulting background subtracted spectrum in the range between 970 Å and 1050 Å is shown in Fig. 2 with the ions producing the detected lines indicated. The recorded spectrum is dominated by OI lines at 988.77 Å and 990.20 Å , and the HI line at 1025.72 Å, both of which contain very significant geocoronal contributions. In principle, geocoronal and stellar lines can be distinguished from their line widths, however, since AB Dor is rapidly rotating, the stellar line profile is unfortunately expected to have about the same width as geocoronal lines. In particular, the Ly_β line is expected to contain a significant stellar contribution, but in view of the above difficulties we chose not to attempt to disentangle geocoronal and stellar contributions to the line profiles. The lines undoubtedly due to stellar emission without any significant geocoronal contamination are CIII 977 Å and the OVI 1032/1038 Å doublet, which appear as weak albeit significant line detections. We note in passing that in the other spectrometer channels line detections were also obtained (in particular the He I 584 Å line in first and second order), however as for Ly_β, disentangling stellar from geocoronal emission is non-trivial.

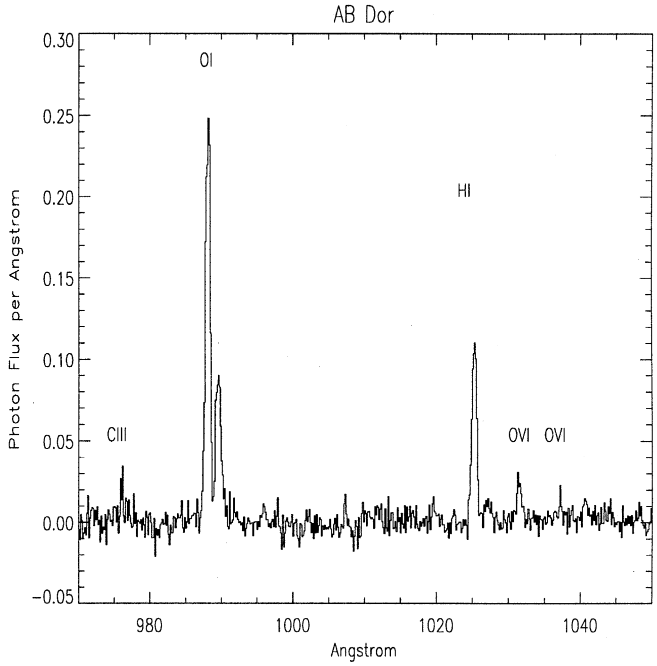

Fig. 2. ORFEUS spectrum of AB Doradus in the wavelength range 960 Å to 1060 Å. The line identifications of the prominent lines are indicated.

3. Spectral analysis of the FUV lines

In order to analyse the recorded ORFEUS spectra, we employed the same technique as used by Schmitt *et al.* (1996) in their analysis of the EUV spectrum of the nearby star Procyon. The results for the derived line fluxes are summarized in Table 2, where we give the line identifications, the recorded apparent photon fluxes and the resulting line luminosities. Note that all the fluxes have been derived assuming a Gaussian line width of σ = 110 km/sec (see below).

3.1. Analysis of the detected FUV lines

In Fig. 3 we show an enlargement of our ORFEUS AB Dor spectrum in the wavelength range between 1028 Å to 1034 Å . The OVI line at 1032 Å is clearly detected in the spectrum. Also shown in Fig. 3 are best model fits to the observed line profile if the measured line profiles of OVI 1032 Å are modeled with a Gaussian at central wavelength λ_{cen}, line strength A, and width

Table 2. Detected FUV lines and fluxes

Line	Wavelength Å	Effective area cm^2	Photon flux sec^{-1} cm^{-2}	Log Luminosity (erg s^{-1})	remarks
CIII	977	3.75	1.64 10^{-2}	28.40	
L_β	1026	4.10	9.5 10^{-2}	29.14	geocoronal contamination
OVI	1031	4.10	2.30 10^{-2}	28.52	
OVI	1038	4.05	1.14 10^{-2}	28.21	

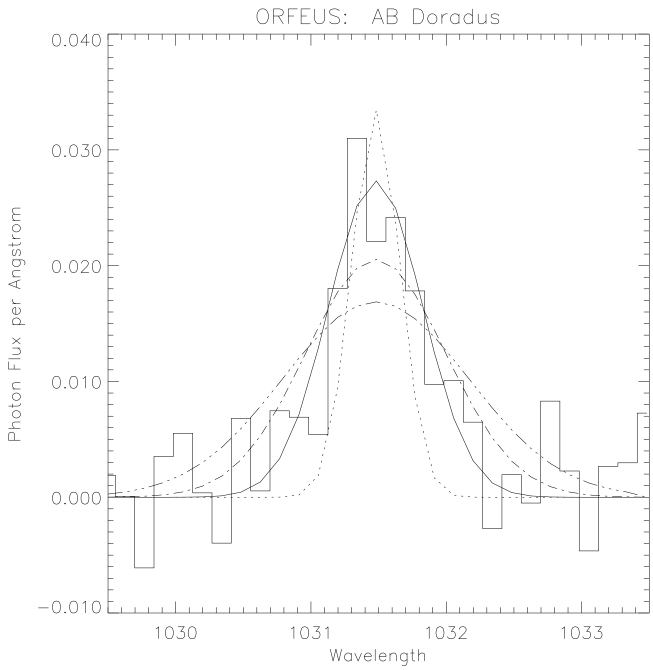

Fig. 3. ORFEUS spectrum of OVI 1032 Å in AB Doradus. Also shown are fits assuming a Gaussian line profile with widths of 50 km/sec (dotted), 110 km/sec (solid) , 150 km/sec (single dot dashed) and 200 km/sec (triple dot dashed) respectively .

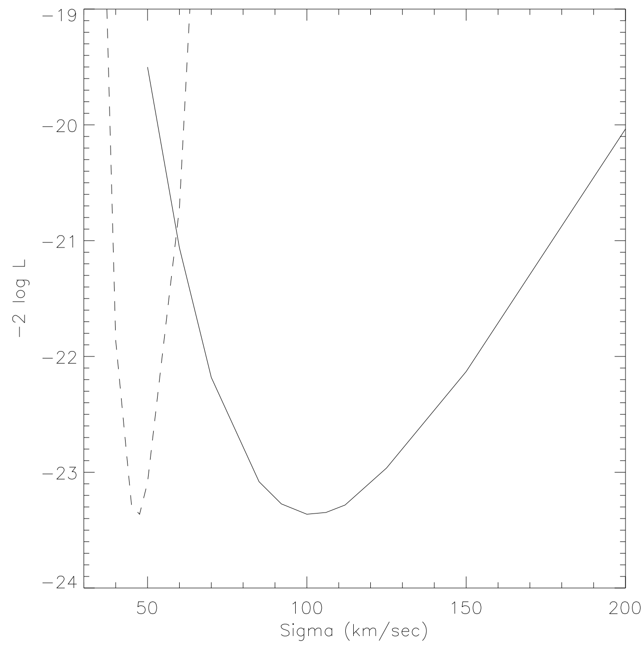

Fig. 4. Best fit likelihood of a Gaussian line profile for OVI 1032 Å vs. σ (in km/sec); solid line displays the results for AB Dor, the dashed line the analogous ones for ϵ Eri.

σ. Fig. 3 suggests that widths below 70 km/sec are simply too narrow to explain the profile, while widths in excess of 120 km/sec are too broad. This finding can be more formalized by plotting the best fit's maximum likelihood (multiplied by -2) as a function of σ plotted in Fig. 4. For comparison we also plot (as a dashed line) the ORFEUS OVI line profile of the slow rotator ϵ Eri, which may be used as a template for the instrumental line profile. Clearly, AB Dor's OVI profile is much broader than that of ϵ Eri. We also attempted to model the ORFEUS OVI line with two Gaussian components with the instrumental width and separated by an adjustable velocity separation; also in this case the best fit velocity separation turned out to be of the order of photospheric value of $v\ sin(i)$. Obviously, our choices to describe the observed line profile are by no means unique. Since there are only $\sim$ 3-4 resolution elements over the line width, many other choices are possible. Nevertheless we think that it is both suggestive and reasonable to ascribe the observed line broadening to AB Dor's rapid rotation.

The same analysis as for OVI 1032 Å was also carried out for the CIII line at 977 Å and Ly_β line at 1026 Å in order to determine line flux estimates. Although the CIII line is clearly detected in the ORFEUS spectrum (cf., Fig. 2), we were not able to derive stringent limits to any line broadening because of the lower SNR of this line. Therefore the line is consistent with being broadened only by the "photospheric" broadening of v sin(i) = 95 km/sec, but it would also be consistent with a variety of other models. The Ly_β line is quite strong (cf., Fig. 2), and the best Gaussian line profile fit is obtained with σ_{line} = 95 km/sec consistent with the derived OVI line width. However, other definitely geocoronal lines also show the same line widths, and therefore we cannot claim to have demonstrated rotational broadening of the Ly_β line in AB Dor.

3.2. Emission measure analysis

In this section we consider the overall emission measure distribution in AB Dor's corona at the time of the ORFEUS FUV observations. Using the emissivities of Raymond & Smith (1977) and adopting a distance towards AB Dor of 25 pc, we can calculate the required emission measure EM to produce the observed CIII and OVI emission as function of temperature (dotted lines in Fig. 5), if the observed line flux is assumed to come from an isothermal plasma; the loci of the minimal emission measures which the maxima in the contribution function are also marked. Also indicated are the emission measures and temperatures of the best fit solar abundance two-temperature model; a dashed line, which is not a best fit, indicates a line with the slope of 1.5. Clearly, our simultaneous FUV and X-ray data are not sufficient to perform a proper differential emission measure analysis, but it is obvious that the emission measure must be rising steeply between temperatures of $logT \sim 5$ and $logT \sim 7$.

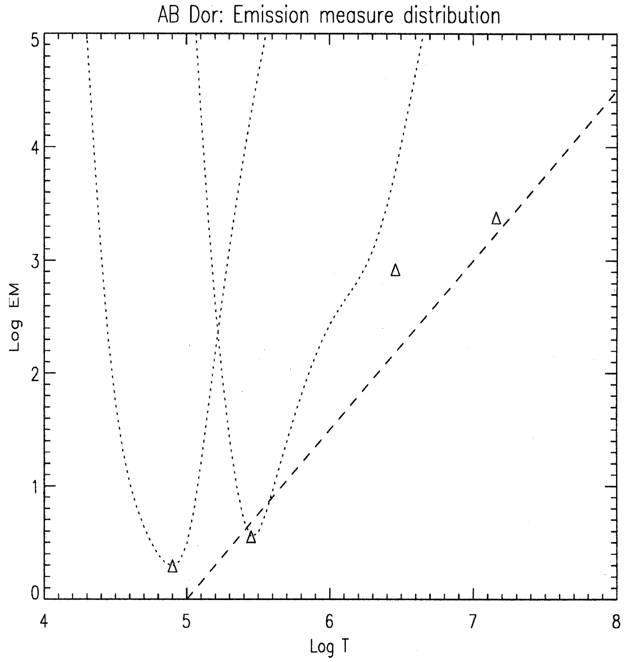

Fig. 5. Emission measure distribution in AB Dor (in units of 10^{50} cm^{-3}) vs. temperature. Shown are the EM values from the ORFEUS detected lines of CIII and OVI as well as the simultaneously measured PSPC temperature components. The dashedline does not represent a best fit but rather indicates a line with a slope of 1.5. The dotted lines give the temperature dependent loci of emission measure if the observed line fluxes are produced by isothermal plasma. The upward triangles indicate the minimally required emission measure values corresponding to the maxima in the line contribution functions.

4. Discussion

A comparison of the X-ray flux level at the time of the ORFEUS AB Dor observations with the long-term monitoring time series by Kürster *et al.* (1997) shows that AB Dor was in one of its most active states ever observed. Nevertheless it is not clear that this high state should be ascribed to a flare event. From Fig. 5 it is clear that the overall emission measure is likely to be rising over a temperature range of at least two decades. Obviously, from our limited data we cannot exclude bi-modal or other multi-component emission measure distributions. We will adopt a simple power-law distribution of emission measure as a working hypothesis, i.e., we assume $EM(T) \sim T^{\alpha}$ with the slope α to be determined from the data. With this assumption a significant fraction of the total OVI line emission will actually be produced from emission measure located not at the peak of the OVI line contribution function at $log\ T = 5.50$ (cf., Fig. 5), but from emission measure located at higher temperatures. For example, test calculations for OVI 1032/1038 Å show that for slopes of α between 1 and 2 a quarter of the total line emission comes from temperatures above log T = 5.6 and log T = 5.8 respectively, so that we can consider the OVI line at least as a partially coronal line. Line profile calculations show that the thermal width of the OVI line yield a FWHM of 30 km/sec, which is smaller than both the instrumental width ($\approx$ 45 km/sec) as well as the expected rotational line broadening. It is therefore very suggestive to attribute the main line broadening to rotation, but we can of course not exclude line broadening due to the flare-like event. Our analysis of sect. 3 shows that the bulk of the material shining in the OVI line has indeed radial velocities which are rather similar to the respective photospheric values; this agreement would have to be coincidental if the flare contributed significantly to the observed line broadening.

While the most straightforward interpretation of the OVI emission is to assume its origin in a thin layer near the photosphere of AB Dor, we also wish to address the question whether the observed OVI line profile is consistent with the idea that cool material (T $\approx 10^4$ K) is formed via condensation from hot material (T $\approx 10^7$ K) at a few stellar radii. From their H_{α} time series Collier-Cameron and Robinson derive an average cloud mass of $2 - 6\ 10^{17}$ g per cloud and a typical number of 5 - 20 clouds present at any given time. Thus the total mass (in mostly neutral hydrogen) amounts to $1 - 12\ 10^{18}$ g and the cloud removal time is of the order $\approx$ 2 days. If one assumes equilibrium, the cooling time of the X-ray emitting gas must then also be $\tau_{rad} \approx$ 2 days; if we further assume that the gas cools predominantly by radiation, we can calculate the density necessary to equate radiative cooling and cloud removal time scales. Using the formula $\tau_{rad} = \frac{3kT}{nP(T)}$ (cf., Schmitt *et al.* 1987), where $P(T)$ and n denote cooling function and density as usual, we find $n \approx 3\ 10^9$ cm^{-3} when assuming $T \sim 2\ 10^7$ K. The total volume V_{X-ray} of the X-ray emitting gas will then be $V_{X-ray} \approx 10^{34}$ cm^3, which implies that a shell with a radius of about two stellar radii is completely filled with X-ray emitting plasma. Therefore, if this plasma were to extend to, say, five stellar radii, either the filling factor would have to be < 10 percent, or the density would have to be smaller. It is interesting to note that such a scenario would actually be consistent with the loop scaling laws. Using $n \sim 10^9$ cm^{-3} and $T \sim 2 10^7$ K we find $p \sim$ 5dyn, which would require loop lengths of $L_{loop} \sim 7.7\ R_*$, however, such large lengths make it difficult to understand the fact that part of AB Dor's X-ray emission is rotationally modulated as reported by Kürster *et al.* (1997).

We can finally compare the total cloud mass with the mass of the X-ray emitting plasma, which is presumed to eventually cool into this mostly neutral gas. Using EM = 10^{53} cm^{-3} and n = 10^9 cm^{-3}, one finds M_{X-ray} = 1.7 10^{20} g, and larger densities lead to smaller masses. This is somewhat larger than the estimated total mass in the form of cool H_α-scattering clouds, but in view of the uncertainties in all the parameters this difference can hardly be considered significant. Thus a reasonably consistent physical picture emerges for densities of a few times 10^9 cm^{-3} for the X-ray emitting plasma; significantly smaller densities lead to an extent of the X-ray emitting plasma significantly in excess of the pressure scale height and significantly in excess of the presumed cloud formation distance. Larger densities on the other hand lead to significantly enhanced cooling, and also make it difficult to understand why the cool material forms at large distances from the star's surface.

To what extent do our ORFEUS observations of the OVI line profile lend support to the above cooling scenario as envisaged by Collier-Cameron aand coworkers, who envisage the cooling from hot X-ray emitting loops to the cool neutral clouds scattering photospheric H_α-radiation to take place at distances of a few stellar radii ? It is rather difficult to estimate the emission measure radiating in the OVI line since we do not know at what density the cooling takes place. Collier-Cameron & Robinson (1989) estimate cloud densities between 10^9 cm^{-3} and 10^{13} cm^{-3} depending on the cloud temperature. Interestingly, the lower cloud densities derived by Collier-Cameron & Robinson (1989) correspond to the lowest reasonable densities of the X-ray emitting plasma and would imply isochoric cooling; on the other hand, density increases by a couple of orders of magnitude can by no means be excluded. In addition to the density dependence, the characteristic cooling time scale depends on the ratio $P(T)/T$, which changes between log(T) = 7.2 and log(T) = 4.50 by about three orders of magnitude, so under the most favorable circumstances one would expect the same number of orders of magnitude less emission measure in order to obtain a steady state. This is roughly consistent with observations, however, since the X-ray and FUV emitting plasma is thought to be magnetically confined, one would expect at least part of this plasma to be located at large radial velocity. Yet the observed OVI line profile, which is likely to even contain coronal contributions, does not show any evidence for such excess broadening. We therefore conclude that the OVI line formation (and by implication that for CIII also) is likely to take place relatively close to the surface as expected from plasma confined in a magnetic loop, but not at distance of a few stellar radii. This does not necessarily exclude the condensation scenario envisaged by Collier-Cameron and coworkers; in particular, if the density increases during cooling, as one would naively assume, it is easy to "hide" the required rather small amounts of emission measure in the high velocity wings of a noisy line profile.

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