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K emission line widths in the Sun and the stars

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Summary. *K* emission line widths measured with a micrometer on integrated spectra of the Sun have a mean value of 38.2 km/s. A definition is proposed whereby the width is a measure in km/s at the e^{-1} value of the difference between the intensity of the brighter K_2 peak over the K_1 background, reckoned from this latter level. Averaged spectra over different parts of the solar disc show the very appreciable contribution by rotation to the emission line width, making it imperative for any calibration of width with absolute magnitude to use a solar value derived from an integrated spectrum. Arguments are presented showing that the *K* emission profile observed in other stars is the profile of the typical bright mottle that should enable the derivation of chromospheric parameters. From measures of Doppler displacements of both K_2 and K_3 'dark condensations' as seen on the Sun are at play in the atmospheres of stars with *K* emission.

1 Introduction

The relationship between the widths of the central emission components present in the *H* and *K* absorption lines of Ca II and luminosity, observed in several stars of late spectral type (Wilson & Bappu 1957), is of considerable astrophysical interest, besides holding forth much promise as a reliable source of measurement of stellar luminosity. Subsequently Wilson (1959) has derived a calibration for absolute visual magnitude utilizing *K* emission line widths of the Sun and the giants in the Hyades.

Such a relation has the advantage of an empirical calibration where the distances of the objects involved can be assumed to be known with accuracy. A point against it is that one discounts the possibility of any anomalies that may be prevalent in the atmospheres of either the Sun or of the giants in the Hyades, which would cause a deviation of the calibration from a common relationship derived for a large sample of objects. There undoubtedly would be many aspects in a stellar atmosphere that can create a certain amount of cosmic scatter in any astronomical relationship and the *K*-line width absolute magnitude relationship is probably no exception to such a possibility. Wilson's weighted solution from trigonometric parallaxes (Wilson 1967) would, therefore, appear to be a more suitable calibration equation to adopt for the determination of an absolute magnitude of a late spectral type star, given its *K* emission line width.

2 The nature of *K* emission

A high-dispersion and high-resolution spectrum of any part of the solar disc reveals the Ca^+ emission to be mainly confined to localized small areas of large brightness. Bappu & Sivaraman (1971) have identified these streaks of emission seen on the spectrograms with the bright fine mottles visible on K_{232} spectroheliograms. Evidence for such interpretation comes from the study of auto-correlation functions of K_2 intensity variations, the spacing between the bright fine mottles from both spectrograms and spectroheliograms and the 200-s lifetime of the fine mottling. A measure of line widths of these features indicates that the bright fine mottling is principally responsible for the relation between *K*-line widths and absolute visual magnitude, discovered by Wilson & Bappu (1957). The fine mottles have a wide range of individual behaviour. While most of these bright points are typically of the order of 1–2 arcsec in diameter, they display much variety in *V*/*R* aspects of both intensity and velocity. Briefly, the manifestation of two different agencies of absorption produces subtle variations in the I_{K_2V}/I_{K_2R} ratio. The effects of these absorption agencies lie superposed over the normal profile of *K* emission characterized by humps in the violet and in the red caused presumably by the depth dependence of the source function. Also present are the Doppler displacements experienced by each fine mottle. In averaging these effects over a large enough sample one might assume the net *K*-profile to be representative of the Sun as a whole. Wilson & Bappu (1957) utilized for the Sun an averaged spectrum at the centre of the solar disc over a region which was free of plage activity, and values obtained from observational material of a similar kind have been used for the Sun–Hyades calibration.

3 The spectrum of integrated sunlight

In averaging K_{232} behaviour over a finite length of slit of spectrograph we seek to obtain a mean characteristic that can be considered representative of the Sun as a star. Solar *H* and *K* emission lines are too weak to be seen on spectrograms taken at dispersion normally used for the stars. Hence, it becomes necessary to employ dispersions comparable to those used in solar studies and at the same time obtain a spectrum that can be considered as truly integrated.

The Kodaikanal solar tower has the first two mirrors of the coelostat on the tower and the telescope in an underground tunnel in a horizontal position with a fixed third mirror to deflect the vertical beam in the tower to the lens of the telescope. Our technique was to diffuse the light at the third mirror by covering it with a diffusing screen made of white pigment. By retaining the rest of the optics in the train we ensure no preference for any one portion of the solar disc over the other. We believe that this technique gives us a real integrated spectrum of the Sun. Calibration and subsequent spectrophotometry have followed the procedure outlined earlier (Bappu & Sivaraman 1971). We also have for comparison, integrated spectra obtained by the technique adopted by Severny (1969). There is no difference that we notice between the profiles obtained by the two methods, and their widths measured according to our definition (next Section) agree to within 0.1 km/s. Exposure times for the method using a scattering surface along with image forming optics are of the order of 150 min on 103a-O film; those for the sunlit sky with no imaging system ahead of the spectrograph are in the neighbourhood of 15 s. That, two such diverse experimental arrangements yield the same value of the measure ensures confidence in the significance of the emission line width obtained.

The average normalized profile of the integrated Sun thus obtained in the sixth order of the grating at a dispersion of 9.4 mm/Å on five different occasions can be seen in Fig. 1. In the same diagram we display the profile obtained by averaging over the entire slit of the individual scans of K_{232} normalized in wavelength with reference to the line Fe I 3932.639 Å and in intensity at a point in the K_{1V} profile at 3933.13 Å. This mean profile provides a width that is identical with the value used by Wilson & Bappu (1957) for an earlier plot of the Sun's location on the *K*-line width–absolute magnitude relation.

The differences between the two profiles in Fig. 1 are quite striking especially as regards width which is so important a parameter in the Sun–Hyades calibration. The emission peaks in the integrated case are stronger, wider and more separated than their counterparts in the 'average over the slit' spectrum. The K_3 absorption is also of greater depth than in the 'average' case.

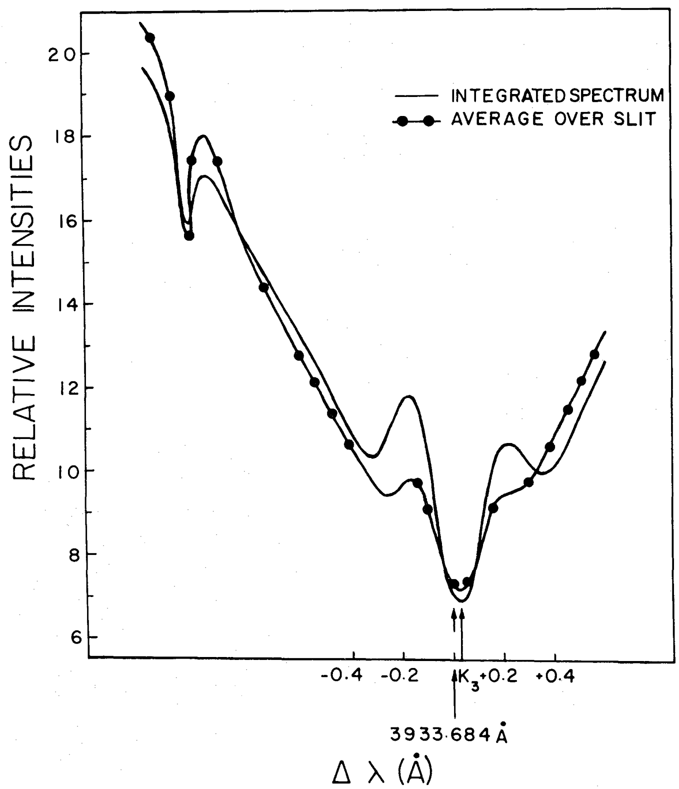

Figure 1. A plot of the mean normalized *K*-line profile of the integrated Sun (mean of five profiles) along with the profile that is the average of several scans at consecutive locations over the entire slit.

4 Proposed definition of *K* line width – $K_{\Delta \mathrm{em}}$

The original Wilson–Bappu measures were made by a micrometer, and consisted of a direct width setting on the emission feature. While this has served the very useful purpose of a preliminary survey, we are of the opinion that in the later dwarf stars where the emission line widths are small, it is necessary to measure with accuracy, especially when the situation prevails wherein different broadening agencies may each contribute to the measured width. A quantitative mode of measurement in accordance with a specific definition would ensure a homogeneous set of data that would be useful in any empirical evaluation. Lutz (1970) has made such an attempt by assuming the profiles to be Gaussian and has determined line widths from them which are found to be in general agreement with *K*-line widths measured by the micrometer, corrected empirically for instrumental broadening. Lutz's study shows up the need for a suitable objective criterion.

We have obtained integrated spectra of the Sun on several different occasions by the technique outlined earlier. These spectra were obtained in both the second and sixth orders of the spectrograph with dispersions of 2.2 and 9.4 mm/Å respectively. One of these at each value of dispersion was used for measures of emission width with the comparator following Wilson & Bappu (1957). Several settings at different positions perpendicular to the dispersion and on different dates, gave a mean value of 38.2 km/s. This width is then stepped off on the intensity profiles of the integrated solar spectrum and the intensity level I_3 established. We find the mean values of the $(I_1 - I_3)/(I_1 - I_2)$ ratio to be 0.63. This is very close to the e^{-1} value of I_1, I_2 difference, reckoned from I_2. In making a measurement of the width of the emission feature with the crosswire of a micrometer the logarithmic response of the eye seems to locate the domain of blackening in the $I_{K_{2V}} - I_{K_{1V}}$ range that is less dense than $I_{K_{2V}}$ by the factor 'e'. Since micrometer measurements of the widths are the principal source of such information, one can formulate a quantitative definition of the width in terms of the eye's response. We propose that $K_{\Delta\,\mathrm{em}}$ be evaluated as the width in km/s at the e^{-1} level of the emission profile. For the solar integrated spectrum $I_{K_{2V}} > I_{K_{2R}}$ and hence we choose the e^{-1} level of $I_{K_{2V}} - I_{K_{1V}}$. Since in the stars, the $I_{K_{2V}}/I_{K_{2R}}$ ratio may be greater or less than 1, we refer the width measures to the e^{-1} level of the brighter of the two with respect to the $I_{K_{1V}}$ or $I_{K_{1R}}$ position. We do so essentially because the less bright emission component could be more affected by absorption than the brighter one, as shown in Section 6.

Support for this definition of $K_{\Delta\,\mathrm{em}}$ comes from a study of intensity tracings of 22 stars that show a range in $K_{\Delta\,\mathrm{em}}$ values. We find the emission line widths measured by Wilson & Bappu (W_{w+B}) to agree with those obtained from the above definition and as shown by the relationship

$$W_{w+B} = 0.99 K_{\Delta\,\mathrm{em}} + 4$$

Table 1 gives the measured values obtained from both comparator settings and the criterion we have defined above.

5 $K_{\Delta\,\mathrm{em}}$ in the integrated spectrum of the Sun

In comparing the values of $K_{\Delta\,\mathrm{em}}$ between the Sun and the stars, the solar value must be from a spectrum that averages the myriad of details normally seen on a calcium spectroheliogram. Wilson & Bappu (1957) had derived this value from a high-dispersion spectrogram obtained by moving the solar image across the slit. Subsequently Wilson (1959) in using a solar value for his Sun–Hyades calibration employed the mean of two plates, one averaged across the solar disk, avoiding the regions of plage activity and the other taken in the sky off the solar image but still adjacent to it. These measures gave a value of 33.3 km/s for $K_{\Delta\,\mathrm{em}}$.

The K emission in the integrated spectrum is visible only when one employs dispersions of the order of 5 Å/mm or higher. The intensity of K is so weak that one needs a much higher dispersion to be able to make a measurement of the line with any accuracy. We have, therefore, employed two dispersions for this purpose so that the lower dispersion would be comparable, in so far as it is possible, with the stellar values and yet is high enough to serve as a check on the value derived from the higher dispersion. Both give us values of 38.0 km/s for $K_{\Delta\,\mathrm{em}}$, with an uncertainty of about 0.5 km/s. We thus find a difference of about 4 km/s from the value used by Wilson & Bappu (1957) and Wilson (1959), as representative of the Sun.

Table 1. Measured values of $K_{\Delta em}$ (km/s).

Star	$K_{\Delta em}$	W_{w+B}
δ And	79	88
β Cet	77	80
36 And	55	56
γ And	111	108
α Ari	72	72
ε Eri	43	42
o^2 Eri	39	47
α Tau	72	86
ι Aur	111	113
α Ori	182	186
δ Vir	84	90
ε Boo	85	98
α Ser	73	76
δ Oph	91	92
α Her	106	114
π Her	92	101
70 Oph	55	48
γ Aql	99	115
γ Sge	89	99
61 Cyg	32	37
λ Aqr	80	96
λ And	72	80

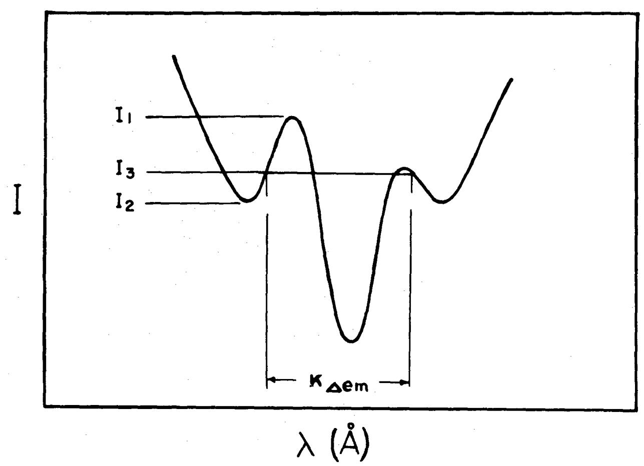

Figure 2. *K*-line emission profile showing the definition of $K_{\Delta em}$.

The difference is easily explained if one assumes that the 1957 and 1959 measures did not pertain to integrated *K* emission over the entire visible disc. The *K*-line profiles increase in width over those at the centre as one samples them for μ values close to the limb. Zirker (1968) has demonstrated these changes in his study of the *K* profiles for different μ values. While this contributes a share to the line widths, the principal contributor will be that of rotation, since the regions farther away from the centre will contribute more to the integrated behaviour than the centre itself. To show the importance of these contributors we have obtained averaged spectra over selected regions on the Sun as shown in Fig. 3. The

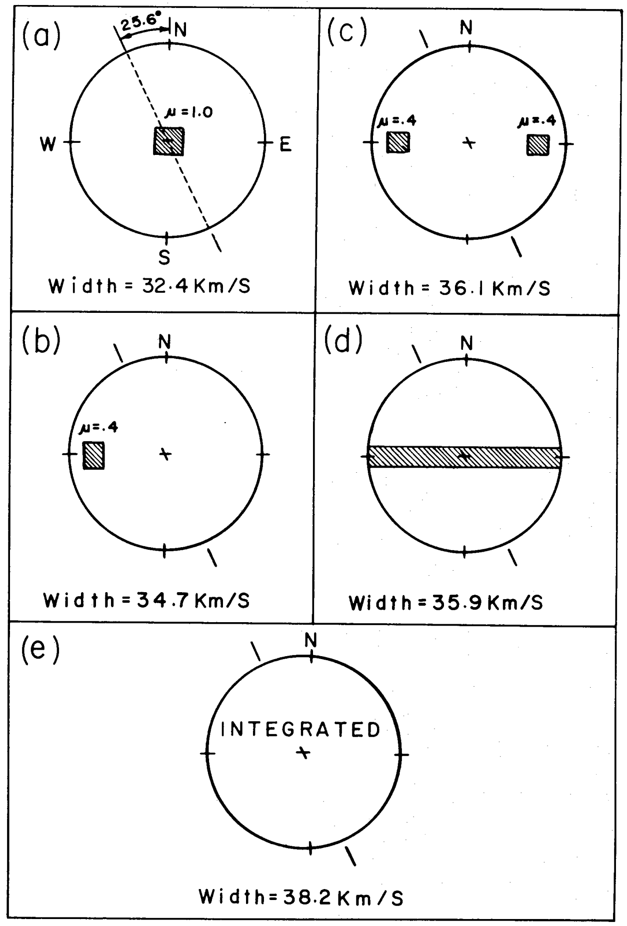

Figure 3. Schematic representation of the different kinds of averaged scans obtainable on the Sun. The shaded areas in (a), (b), (c) and (d) represent the regions on the Sun which contributed to the corresponding average spectra. (e) represents the true integration (see text for details). The width measured from the respective spectra is indicated within each box.

smallest value of $K_{\Delta\,\mathrm{em}}$ is obtained for the averaged spectrum at the centre of the disc. The single area at $\mu = 0.4$ in Fig. 3(b), shows the widening caused by the centre-limb variation. Fig. 3(c) introduces the rotation component into the picture. Here, we have obtained a single exposure that is the summation over two equal time intervals, of averaged scans at $\mu = 0.4$, near both the east limb and west limb of the Sun. An enhanced value of $K_{\Delta\,\mathrm{em}}$ is the immediate result. There is little to choose between this value and that obtained when one scans from limb to limb as has been depicted in Fig. 3(d). A $K_{\Delta\,\mathrm{em}}$ value from Zirker's profile (1968, Fig. 3) at $\mu = 0.6$ is 36.4 km/s. If limb darkening at the wavelength of the K emission is assumed to be minimal, the integrated spectrum is representative of the solar emission profile near $\mu = 0.7$. The $K_{\Delta\,\mathrm{em}}$ value at this position will be slightly less than 36.0 km/s. If one adds to this value the equivalent rotational velocity at $\mu = 0.7$ of 2.8 km/s one obtains as an upper limit 38.8 km/s for $K_{\Delta\,\mathrm{em}}$. This value is reduced a little, as limb darkening becomes significant.

These experiments show how the increases in width of the averaged K_{232} profile arise from different contributions, especially that due to rotation. It is essential, therefore, to employ the integrated spectrum for any comparison of solar behaviour with that seen elsewhere in the stars.

6 A comparison with the stars

At dispersions normally used for obtaining stellar spectra, one would certainly not see the K_2 reversal in the case of the solar chromosphere. An age effect pointed out by Wilson & Skumanich (1964) is operative that causes the intensities of reversal to be so small as to be detectable only at high dispersion. There are, nevertheless, many stars for which K-line widths have been measured (Wilson & Bappu 1957; Warner 1969; Wilson 1976) and which follow the width–absolute magnitude relation. Since the Sun follows this relation and since we have earlier (Bappu & Sivaraman 1971) identified the agencies on the solar surface responsible for this behaviour, it is reasonable to assume that similar manifestations in stellar chromospheres, but of varying degree and greater intensity, are operative. A comparison of the K_{232} profile in the integrated spectrum of the Sun with similar profiles of the bright mottles, shows at a glance that the integrated case is an envelope that is a summation of performance of individual bright mottle profiles along with their Doppler displacements and the contribution of the dark condensations. Since the envelope is a weighted mean, the integrated K profile evaluated in terms of red and violet components is closely similar to that of the typical bright mottle.

The physical parameters controlling the excitation of the bright mottle are those of temperature, density and the velocity effects originating from the convection zone, that together with the magnetic fields pervading the medium, characterize the typical mottle. By treating the red and violet components separately by the methods introduced by Jefferies & Thomas (1960) and followed up by Linsky (1970) a set of parameters defining the chromosphere characteristics are easily derivable.

It is well to realize that another common characteristic on the solar surface, the calcium plage, can compete with the bright mottle for dominance in contribution to the integrated K emission. In the case of the Sun we have shown earlier that by virtue of intensity and area, the role of the plage is a minor one. Two aspects enable us to identify the plage contribution. If stellar plages are also the result of active regions on the surface, then changes in the areal extent would cause intensity changes in the integrated spectrum. Also the K-line widths would be dependent on the magnetic field values and would show up as deviations from the Wilson–Bappu relationship. Monochromatic light curves of variation of the K emission characteristic shows that such changes in intensity are small and that a majority of the stars do not exhibit them. Our information in this regard is, however, very scanty. But all factors point out that the bright mottle or its stellar equivalent is the principal contributor to integrated K emission. Since there is little difference between the emission line profile in the mottle and that in the integrated spectrum, we are in the stellar case, especially where plage activity is ruled out, witnessing the performance of the mottle.

The 'dark condensations' that we have pointed out to be present in the solar chromosphere (Bappu & Sivaraman 1971) have a definitive role in modifying the violet or red intensities of the emission reversal. We have seen them of sizes in the vicinity of 3500 km and with principally down-flowing velocities in the range 5–8 km. In the integrated spectrum of the Sun, the K_3 minimum, which is a combination of the dark condensations as well as the gap between the two K_2 components, has a positive shift of recession when compared to the normal wavelength of the K line. With this background of the solar case we examine K_3 in the stars and in particular whether its displacement has a bearing on the relative intensities of K_{2V} and K_{2R}. If K_3 has a contribution from an agency similar to the dark condensations seen on the sun, then intensities with $V > R$ would be associated with positive values of K_3 displacement and vice versa. Table 2 gives these characteristics for a few stars for which we have available material. The first two columns give the star identification and the MK spectral type. Column 3 gives a visual estimate of the intensity of K emission,

Table 2. Displacements of the absorption and emission components.

Star	Sp	Emission intensity	Brighter component *V* – Violet *R* – Red	Displacement (km/s) Absorption Δa	Emission Δe
δ And	K3 III	2	*V*	−1	+1
β Cet	G6	2	*V*	0	−1
36 And	K1	1	*V*	0	−1
β And	M0 II	4	*R*	−22	−6
η Psc	G8 III	1	*V*	0	0
51 And	K3 III	2	*V*	+1	+1
γ And	K3	2	*R*	−1	−2
α Ari	K2 III	2	*V*	+2	+2
α Tau	K5 III	4	*R*	+2	+6
α Ori	M2 Iab	3	*R*	0	+4
π Aur	M3 II	4	*R*	−18	−4
μ Gem	M3 III	4	*R*	−14	−3
ω Gem	G5 II	2	*V*	+7	−8
α Lyn	M0	3	*R*	−5	−3
α Hya	K3 II–III	3	*R*	0	0
ε Leo	G0 II	2	*V*	0	−3
π Leo	M2 III	3	*R*	−14	−4
37 LMi	G3 II	2	*V*	+2	−2
75 Leo	M0 III	3	*R*	−2	0
33 Vir	K1 IV	2	*V*	0	−1
δ Vir	M3 III	3	*R*	−16	−3
ε Boo	K0 II–III	1	*V*	0	−2
β UMi	K4 III	3	*R*	0	0
37 Lib	K1 IV	2	*V*	0	0
α Ser	K2 III	2	*V*	0	0
τ CrB	K0 III–IV	1	*V*	+2	+2
δ Oph	M0	2	*R*	−8	−4
α Sco	M1	3	*R*	−8	−4
α Her	M5	3	*R*	−6	−4
π Her	K3 II	2	*V*	−1	−2
β Dra	G2 II	3	*V*	+7	+2
ξ Dra	K2 III	2	*V*	+1	+1
γ Aql	K3 II	3	*R*	−3	−1
γ Sge	M0	1	*R*	+1	0
ε Cyg	K0 III	2	*V*	+1	0
ε Peg	K2 Ib	4	*R*	−34	−6
α Aqr	G2 Ib	2	*R*	−2	+2
ζ Cep	K1 Ib	3	*R*	−28	−3
35 Peg	K0	2	*V*	−1	−3
λ Aqr	M2	4	*R*	−10	+2
β Peg	M2 II–III	4	*R*	−8	−2

followed by column 4 which indicates the brighter of the two emission components, violet (*V*) or red (*R*). Columns 5 and 6 headed 'Δa' and 'Δe' contain values of displacement in km/s of the absorption component (K_3) and of the mean K_2 emission, obtained from Wilson & Bappu (1957, Table 3).

Of 41 stars in our list for which we are able to make V/R estimates, 32 stars have Δa values that differ from Δe. Thirteen of these stars have more positive displacements of Δa with respect to Δe and 19 stars have Δa more negative than Δe. If the Δa displacement is more positive than that of Δe, one would expect, if K_3 is caused by absorption, to find that $V > R$ for the K_2 intensities. The reverse situation between Δa and Δe will provide $V < R$. Out of 32 stars indicated above 29 have observed V/R in conformity with our expectation from the Δa, Δe values. Nine of the remaining stars have $\Delta a = \Delta e$ within the accuracy of measurement. Seven of these have $V > R$, indicating the possibility of $K_{2V} > K_{2R}$ as a normal occurrence. The same is true in the case of the Sun. The seven stars range in spectral type from G0 III to K3 III. δ And has $V > R$ with a value Δa more negative than Δe. γ Sge and γ And have $R > V$ with a value of Δa more positive than Δe. There is evidence that there are V/R changes in the emission observed in the latter case.

The agreement between the observed V/R and that expected from the relative displacements of Δa and Δe indicate a primary contribution of moving absorbing matter to the K_3 feature similar to the dark condensations we have seen in the solar chromosphere.

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