COMPARISON OF Hα AND Ca II H AND K SPECTROHELIOGRAMS AS A DIAGNOSTIC PROBE

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Abstract. The line formations of Hα and Ca II H and K are compared in order to differentiate the various mechanisms giving rise to observable contrasts in the emergent intensities. Table II summarizes the criteria for distinguishing between horizontal spatial variations in temperature, density, and turbulent velocity.

1. Introduction

Spectroheliograms taken in the light of Hα are readily distinguished from those in Ca II H and K both by their overall appearance and by many of their specific details. Figures 1a and 1b are spectroheliograms taken simultaneously in the line centers of Hα and Ca II K. Comparison of these figures shows that whereas some features, such as filaments and plages, appear in both spectroheliograms, others, like the dark fibrils seen in Hα, do not appear in Ca II K, while still others are seen in Ca II K and not in Hα. These features, or contrasts in the emergent intensity, may arise directly from lateral changes in electron temperature, T_e, or in electron density, N_e, or from changes in the shape of the absorption profile such as could result from mass motions or from changes in T_e or in turbulent velocity. In this paper, we suggest how the differences between the Hα and Ca II H and K spectroheliograms may be used, together with a knowledge of the physical processes by which each line is formed, to distinguish the various mechanisms giving rise to the observed features. Here, however, we exclude from our discussion features such as prominences that arise from systematic mass motions (Hyder and Lites, 1970). Our theory is based on the supposition that Hα and Ca II are formed in roughly the same regions of the chromosphere (Vernazza *et al.*, 1973).

2. The Line Formation

The physics involved in the formation of any given line depends on the dominant processes by which line photons are created and destroyed (Thomas, 1965). A new line photon is created in the radiation field when the upper level of the transition is excited from the lower level either by direct collisions or by indirect processes, which are usually photoionizations from the lower level followed by photorecombinations to the upper level. Similarly, line photons in the radiation field are destroyed either by direct collisional de-excitations or by indirect processes. Whether direct collisions or photoionizations dominate these *source* and *sink* processes depends, *for a given*

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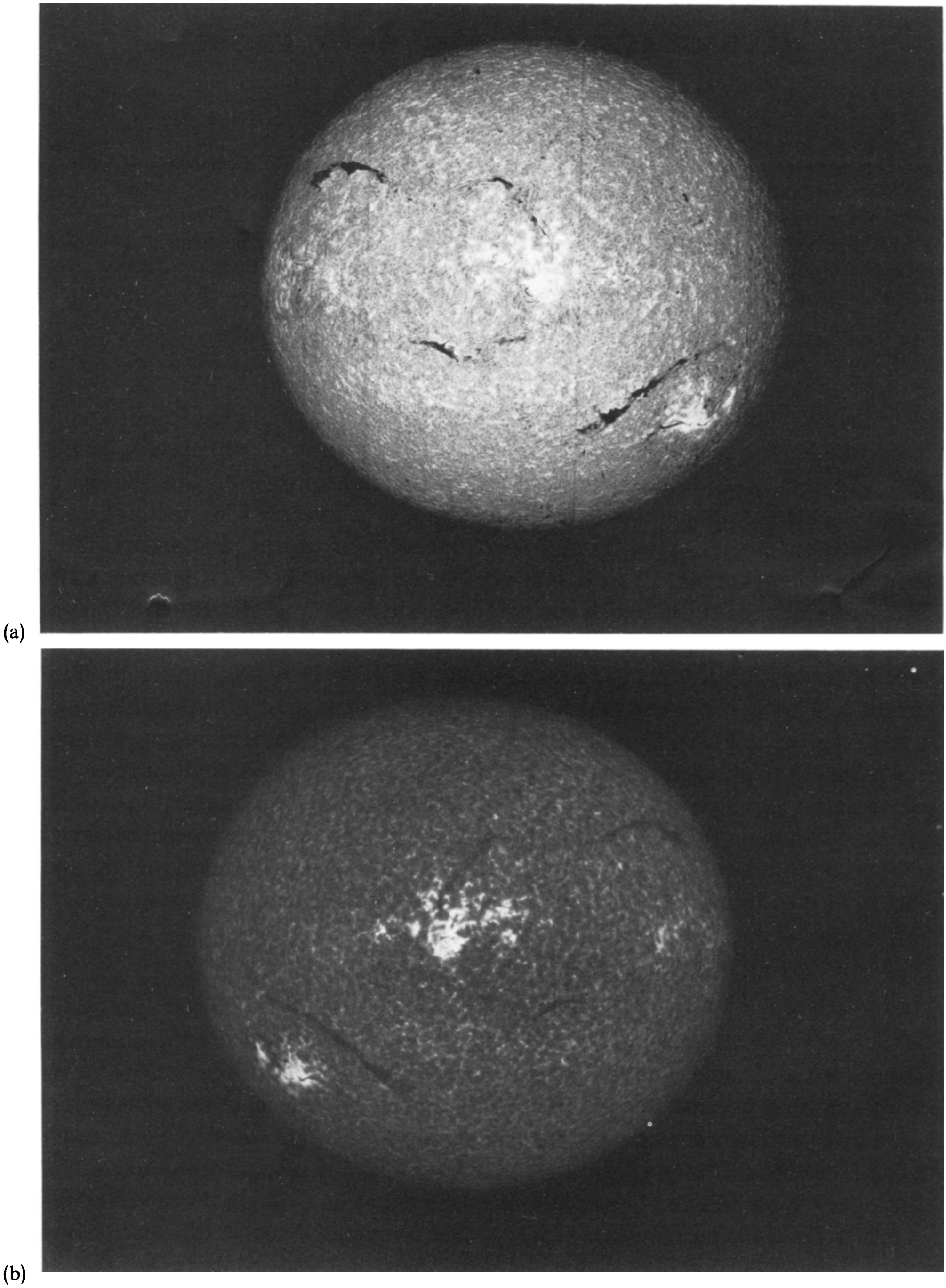

Fig. 1. **Spectroheliograms in (a) Hα and (b) Ca II K, taken at line centers on 1973, May 25 at 13:22: UT.** Note the fine detail that appears in Hα but not in Ca II K. (Sacramento Peak Observatory, Air Force Cambridge Research Laboratory.)

transition, on the electron density, the collision cross sections, and the intensity of the ionizing radiation fields.

The essential difference between the formation of Hα and that of Ca II H and K in the solar chromosphere may be understood from a comparison of their energy level diagrams (Figure 2). For Hα, the upper and lower levels of the transition are only 1.5 eV and 3.4 eV, respectively, below the continuum. Thus the solar radiation fields in the Balmer and Paschen continua suffice to insure that photoionizations and photo-recombinations dominate over direct collisions as sources and sinks of line photons. Since the Balmer and Paschen continua are fixed in the photosphere, well below the region of Hα line formation, we would not expect any horizontal spatial variation in these source and sink terms. For Ca II H and K, on the other hand, the upper and lower levels of the transition are 8.7 eV and 11.9 eV below the continuum. Because the flux of solar radiation at these energies is low, direct collisions control the creation and destruction of line photons. Since the rate of these collisional transitions depends on electron temperature and density, lateral changes in these parameters will affect the source and sink terms.

Actually, there has been some controversy in the past over whether Hα is collision or photoionization controlled in the solar chromosphere. Using the most recent atomic data to compute and compare the relevant rates, we feel that we have now resolved this controversy in favor of photoionization control. This result is displayed in the form of a source-sink-control diagram, Figure 3 (Gebbie and Steinitz, 1974).

3. The Features

Having distinguished between collision and photoionization controlled lines, we now make the distinction between optically thick and optically thin features.

The emergent intensity at a frequency ν is given by

$$I(\nu, 0) = \int_0^\infty S(\tau)\, e^{-\phi(\nu)\tau}\, \phi(\nu)\, \mathrm{d}\tau, \tag{1}$$

where τ is the optical depth in the line center, $\phi(\nu)$ is the normalized absorption profile *assumed independent of depth*, and $S(\tau)$ is the frequency independent line source function, which may be written

$$S(\tau) = \frac{\int_0^\infty J(\nu, \tau)\, \phi(\nu)\, \mathrm{d}\nu + \text{sources}}{1 + \text{sinks}}. \tag{2}$$

Here the first term in the numerator is the so-called scattering term, and $J(\nu, \tau)$ is the mean radiation field given by

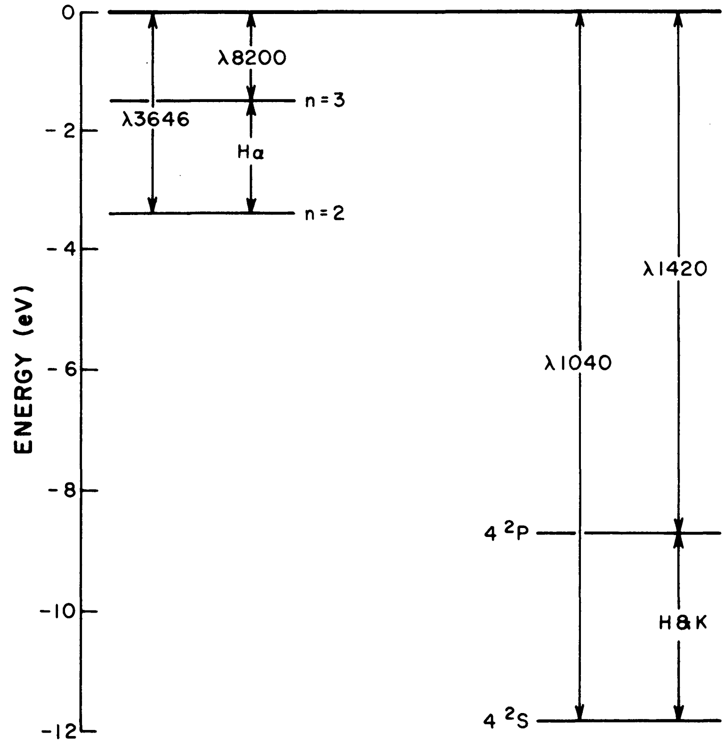

Fig. 2. A comparison of Hα and Ca II H and K energy level diagrams. The Hα transition is 2→3, and the Ca II H and K is $4^2S_{1/2}\rightarrow 4^2P_{1/2,\,3/2}$.

$$J(\nu,\tau)=\tfrac{1}{2}\int_{0}^{\infty} S(t)\,E_1\,|\phi(\nu)\,(\tau-t)|\,\mathrm{d}t. \tag{3}$$

Because most 'photon encounters' are in fact scatterings, $S(\tau)$ is numerically equal – to within about one percent – to the value of the scattering term, which is itself determined by the ambient radiation field in the line.

We define a feature as a lateral inhomogeneity that gives rise to an observable contrast, $C(\nu)$, defined as follows:

$$C(\nu)=\frac{I_f(\nu,0)}{I_0(\nu,0)}-1, \tag{4}$$

where $I_f(\nu,0)$ and $I_0(\nu,0)$ are, respectively, the observed intensities of the feature and the featureless regions.

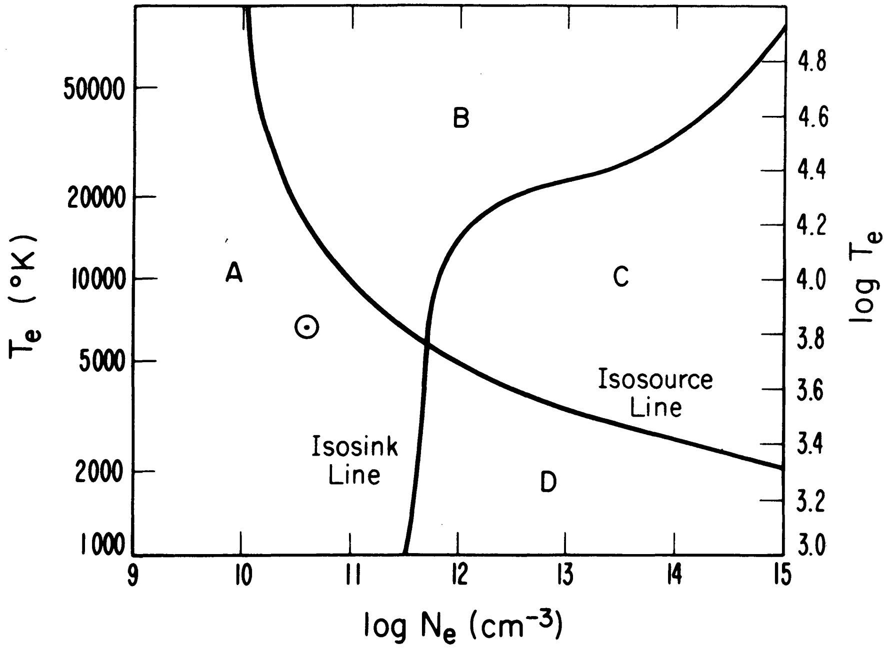

Fig. 3. Source-sink-control diagram for Hα and a radiation temperature of 5800 K. The isosource line delineates those values of T_e and N_e for which the rate of creation of line photons by direct collisional excitations equals that by indirect processes; the isosink line is that on which the rate of destruction of line photons by direct collisional de-excitations equals the rate by indirect processes. *Zone A:* sources and sinks indirectly controlled; *Zone B:* sources controlled by direct collisions; sinks indirectly controlled; *Zone C:* sources and sinks controlled by direct collisions; and *Zone D:* sources indirectly controlled; sinks controlled by direct collisions.

The Sun has been placed at $T_e = 6500$ K and $N_e = 4 \times 10^{10}$ cm^{-3} in accordance with the model of Vernazza *et al.* (1973).

3.1. OPTICALLY THICK FEATURES

In an optically thick feature, the source function builds up its own self-consistent radiation field, in the sense that Equations (2) and (3) are coupled to yield an equation of the form

$$S(\tau) = \frac{1}{1 + \text{sinks}} \int_0^\infty K(t, \tau; \phi)\, S(t)\, \mathrm{d}t + \frac{\text{sources}}{1 + \text{sinks}}, \tag{5}$$

where $K(t, \tau; \phi)$ is the kernel. As long as the absorption profile is fixed and independent of depth, the solution, $S(\tau)$, depends only on the τ dependence of the source and sink terms.

Thus in a collisionally controlled line, where the sources and sinks are affected by lateral differences in the depth distribution of T_e and N_e, we would expect such differences to be reflected as contrasts in the emergent intensity. In a photoionization controlled line, however, such differences in T_e and N_e will not be observed, provided the ionizing radiation fields are fixed outside the region of line formation.

3.2. OPTICALLY THIN FEATURES

In an optically thin feature, Equations (2) and (3) are *uncoupled*: instead of building up its own radiation field, such a feature 'sees' the radiation field of the surrounding, featureless region. Thus the scattering term, and hence the source function itself, are determined not by the distribution of source and sink terms inside the feature but by those in the surrounding region. In contrast to the optically thick case, therefore, the source and sink terms inside the feature have almost no effect on the emergent intensity, regardless of whether the line is collision or photoionization controlled. Thus, in an optically thin feature, the source function is a function of geometrical rather than of optical depth.

There are, however, two mechanisms that may, in optically thin features, give rise to contrasts in the observed intensity.

(1) A change in the density will introduce a shift in the optical depth scale. The effect of such a shift on the emergent intensity will then depend on the behavior of S as a function of τ. If, for example, the density is lower in the feature than in the surrounding region, the optical depth at a given geometrical level of the atmosphere will be lower; the main contribution to the integral $I(\nu, 0)$, Equation (1), will then come from deeper levels of the atmosphere, where the source function has, in general, a higher value. Thus the feature will appear brighter than its surroundings at *all frequencies* in the line profile. If, on the other hand, the density is larger in the feature than in the featureless region, we will 'see' values of the source function higher in the atmosphere, and the feature will appear darker at all frequencies. In neither case will there be a reversal of sign in the contrast profile. That is, a feature that, as a result of a change in density, appears bright at line center will appear bright in the wings, and correspondingly, a feature that appears dark at line center will appear dark in the wings.

(2) A change in the shape of the *normalized* absorption profile, $\phi(\nu)$, will in general affect the emergent intensity in two ways: (i) by changing the value of the scattering term in the source function, and (ii) by introducing a frequency dependent shift in the optical depth scale (Gebbie and Steinitz, 1973 a, b). The effect on the scattering term will depend on (a) the relative shapes of the absorption profiles inside and outside the feature and (b) the frequency dependence of $J(\nu, \tau)$ at the depth of the feature. The effect of the shift in the optical depth scale will, as when resulting from a change in density, depend on the shape of the source function. However, since the profile is normalized, there will be some frequencies at which the profile has a larger value in the feature than in the non-feature and other frequencies at which it has a lower value. Thus we predict a reversal of sign in a contrast profile produced by this mechanism. Such reversals have in fact been observed by Grossmann-Doerth and Von-Uexküll (1971, 1973), by Bray (1973), and by Bar *et al.* (1973).

This discussion clearly includes such special cases as Becker's (1964) cloud model and de Jager's (1957) mottle models.

3.3. GENERAL CLASSIFICATION

In the previous sections we have classified line formation according to the processes controlling the source and sink terms and according to the optical thickness of the feature. This general scheme is summarized in Table I, which is self-explanatory. In the following section, we apply this scheme to the formulation of criteria by which to distinguish the various mechanisms giving rise to the observed contrasts.

TABLE I

Mechanisms for producing observed contrasts
(excluding systematic mass motions)

	Optically thick feature		Optically thin feature
Primary change	$S(\tau)=\frac{1}{1+\text{sinks}}\int_0^\infty K(t,\tau;\phi)\,S(t)\,\mathrm{d}t+\frac{\text{sources}}{1+\text{sinks}}$		$S(\tau)\sim\int_0^\infty J(\nu)\,\phi(\nu)\,\mathrm{d}\nu$
	Collision control	Photoionization control	Control irrelevant
Density, N_e, T_e	changes in source and sink terms	no changes	change in τ scale
$\phi(T_e, v_t)$	(possible change of kernel)	(possible change of kernel)	(1) change of τ scale (2) change of scattering integral

4. The Shape of the Line Profile

Changes in the shape of the line profile may result from changes in temperature or in turbulent velocity, or from mass motions, or from any combination of these mechanisms. In this paper, however, we deal only with stationary features, excluding any discussion of macroscopic velocities.

The effect of changes in temperature and turbulent velocity on the line width may be combined in the following manner. The Doppler width of the line is given by

$$\Delta\lambda_{\mathrm{D}}=\frac{\lambda}{c}\left(\frac{2kT}{m_{\mathrm{A}}}+v_t^2\right)^{1/2}, \tag{6}$$

where m_{A} is the mass of the atom and v_t is the ambient turbulent velocity. For a given spectral line, the Doppler width in a feature of temperature T' and turbulent velocity v_t', relative to that in the featureless region, may conveniently be expressed as

$$\frac{\Delta\lambda_{\mathrm{D}}'}{\Delta\lambda_{\mathrm{D}}}=\left(\frac{\theta+\mu\xi'}{1+\mu\xi}\right)^{1/2}, \tag{7}$$

where all velocities have been normalized with respect to the thermal velocity of hydrogen at the temperature T in the featureless region. Thus $\theta'=T'/T$, $\mu=m_{\mathrm{A}}/m_{\mathrm{H}}$,

$\xi = v_t^2/(2kT/m_H)$, and $\xi' = v_t'^2/(2kT/m_H)$. Here it is the mass of the atoms ($\mu_H = 1$, $\mu_{ca} = 40$) that will distinguish the effects of changes in T and v_t on Hα and Ca II H and K. For turbulent velocities of the order of the thermal velocity of hydrogen, changes in temperature will have negligible effect on the calcium absorption profile but can be significant for hydrogen. Changes in the turbulent velocities, on the other hand, will tend to have a greater effect on calcium than on hydrogen.

One may therefore expect changes in temperature to be reflected in contrasts observed in Hα but not in Ca II H and K, whereas changes in turbulence should be observed in both lines.

5. Summary: The Criteria

We now classify the observed contrasts according to two criteria: (1) Is the feature seen in Hα but not in Ca II H and K, or is it seen in both lines, or is it seen only in Ca II H and K? (2) Is there a reversal of sign in the contrast profile? These criteria are applied in Table II to distinguish between changes in electron temperature, density, and turbulent velocity. We distinguish systematic mass motions by asymmetric and shifted profiles.

TABLE II

Criteria for distinguishing the mechanisms (excluding systematic mass motions)

Contrast seen? Hα	H and K	Sign reversal in contrast profile?	Optical thickness	Operative mechanism
yes	no	yes	thin	ΔT_e
yes	yes	yes	thin	Δv_t
yes	yes	no	thin	Δ(density)
no	yes	[a]	thick	$\Delta T_e \; \Delta N_e \; \Delta v_t$

[a] depends on the details of the particular processes.

Thus by comparing Hα and Ca II H and K spectroheliograms, and by observing the behavior of the contrast as a function of frequency in the line profile, it is possible to probe the conditions giving rise to the observed contrasts. We therefore encourage observers to take spectroheliograms or spectrograms simultaneously in Hα and in Ca II H and K. This could provide data for a more reliable interpretation of the physical conditions prevailing in the solar chromosphere.

Finally, it should be pointed out that conditions in flares and plages may shift the control of Hα formation from photoionizations to collisions; if so, the criteria given in Table II would not be valid.

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References

Bar, V., Steinitz, R., and Gebbie, K. B.: 1973 (in preparation).
Beckers, J. M.: 1964, Thesis, Utrecht.
Bray, R. J.: 1973, *Solar Phys.* **29**, 317.
de Jager, C.: 1957, *Bull. Astron. Inst. Neth.* **13**, 149 (No. 474).
Gebbie, K. B. and Steinitz, R.: 1973a, *Solar Phys.* **29**, 3.
Gebbie, K. B. and Steinitz, R.: 1974, *Astrophys. J.* **188**, 399.
Grossmann-Doerth, U. and von Uexküll, M.: 1971, *Solar Phys.* **20**, 31.
Grossmann-Doerth, U. and von Uexküll, M.: 1973, *Solar Phys.* **28**, 319.
Hyder, C. L. and Lites, B. W.: 1970, *Solar Phys.* **14**, 147.
Thomas, R. N.: 1965, *Some Aspects of Non-Equilibrium Thermodynamics in the Presence of a Radiation Field*, University of Colorado Press, Boulder.
Vernazza, J. E., Avrett, E. H., and Loeser, R.: 1973, *Astrophys. J.* **184**, 605.

DISCUSSION

Wilson: Would you explain exactly what you mean by the reversal in sign?

Gebbie: If, for example, the temperature or turbulent velocity were lower in the feature than in the surrounding region, the normalized absorption profile will be narrower; that is, the profile will have a higher value in the center of the line and a lower value in the wings. Thus provided the feature is optically thin and the source function decreases monotonically outwards, we would expect the feature to appear dark in the center of the line and bright in the wings. This is what we mean by a reversal in the contrast profile.

Athay: Could we see the first slide again? Dr Gebbie points out that she has plotted the sun on her source-sink-control diagram at an electron density of about 4×10^{10} cm^{-3}. If you go down a little deeper in the chromosphere, the electron density increases to something like 2×10^{11} cm^{-3}. You need an electron density definitely above 10^{11} cm^{-3} to get the maximum in the Balmer continuum emission as observed at eclipse. You see the region just above the temperature minimum at about half an angstrom from line center in Hα. Also, you expect to see regions of a little higher density when you go to the network regions. The effect of the higher densities will move your point toward the intersection between photoionization and collision control, and Hα will show some effect of collisions.

Gebbie: Yes, certainly an increase in density will 'move the Sun' *toward* the intersection, but Hα will still be photoionization dominated at densities of up to about 5×10^{11} cm^{-3}. According to the *one-component* model of Vernazza, Avrett and Loeser, this value is not reached until well below the temperature minimum. However, in denser chromospheric regions, such as perhaps flares and plages, collisions will certainly begin to dominate. Also, if, as has been suggested by Milkey, there is a photospheric contribution to the emergent intensity in Hα, this will be affected by collisions.

Giovanelli: Where we see bright features in Hα, we see these usually fairly small points, and when we look in the K line we will find that surrounding these points, we will certainly find it brighter than average in the K line. But surrounding this there will be a region where it is bright in the K line and dark in Hα. Now, would you like to interpret this?

Gebbie: I would interpret the feature that you see in Ca II K and not in Hα as being optically thick. Without further information, I could not then say whether the increase was due to an increase in temperature, density, or turbulent velocity.

Zirin: I guess I disagree with Ron Giovanelli just a little bit. Most of the time when you find the diffuse calcium brightening bigger than in Hα, it's because the calcium filter isn't well aligned. The only difference that I've ever been able to find is close to sunspots where there is overlying absorbing material. This material may be dark in Hα and somewhat transparent in calcium K, and I would say that from every observation I have made that there is only a quantitative and not a qualitative difference between K and Hα except close to sunspots. In the network I've never seen any difference. Even in flares the two are identical, and that's quite a departure in temperature and density from your critical value.