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A Non-LTE Analysis of the Ca II Infrared Triplet as a Diagnostic Tool in Solar-type Stars

I. Busà[1,2], V. Andretta[2], M.T. Gomez[2], L. Terranegra[2]

Abstract.

NLTE calculations of the profiles of the Ca II InfraRed Triplet (IRT: $\lambda = 8498$, 8542, 8662 Å) are performed for a grid of photospheric models with $T_{\rm eff}$=4200, 5200, 6200 K, $\log g$=4.0, 4.5, 5.0 and [A/H]=0.0, -1.0, -2.0, showing the sensitivity of the profiles to changes in stellar parameters and the effect of departures from LTE.

Our analysis shows that the correlation between the observed line central depression and $\log R'_{\rm HK}$ found, for instance, by Chmielewski (2000) is mainly due to the effect of $v \sin \hat{\imath}$ (via the rotation–activity correlation) instead of being the result of a pure chromospheric filling-in of the line core.

We therefore define a new activity index, $R_{\rm IRT}$, given by the difference between the calculated photospheric central intensity and the observed one. The correlation we find between this purely chromospheric index and $\log R'_{\rm HK}$, for which we give two interpolation expressions, is more directly related to chromospheric activity.

1. Introduction

The InfraRed Triplet (IRT) of Ca II at $\lambda = 8498$, 8542, 8662 Å, is one of the most conspicuous features of the near infrared region of the spectra in G, K and M stars. Several authors have underscored the diagnostic power of these lines as activity indicators. Linsky et al. (1979) show for example that the radiative loss rates in the λ8542 Å line is well correlated with radiative loss rates in the Ca II H & K and Mg II h & k lines, while Chmielewski (2000) finds an average relation between the central depth of the observed λ8542 Å line and the $\log R'_{\rm HK}$ indicator. Nevertheless, while the $\log R'_{\rm HK}$ can be considered a pure-chromospheric indicator being derived by subtracting an estimated photospheric contribution, the central depth of the Ca II IRT, usually used as activity indicator, ought to be transformed into another chromospheric emission fraction, also corrected for the effects of the basic atmospheric parameters.

In this poster we show preliminary results of such a correction.

[1]Hamburger Sternwarte

[2]Osservatorio Astronomico di Capodimonte

2. Sensitivity to Stellar Parameters

In order to investigate the sensitivity of the Ca II IRT line profiles to the basic stellar parameters such as effective temperature, gravity and metalicity, we selected from the *NextGen* database (Allard & Hauschildt, 1995) a grid of photospheric models with $T_{\rm eff}$=4200, 5200 and 6200 K, $\log g$=4.0, 4.5, 5.0, and [A/H]= 0.0, -1.0, -2.0.

The coupled equations of radiative transfer and statistical equilibrium were solved for the H and Ca atomic models using the version 2.2 of the code MULTI (Carlsson 1986). The opacity package included in the code takes into account free-free opacity, Rayleigh scattering, and bound-free transitions from hydrogen and metals. Line opacity (line blanketing) has been taken into account with the method described in Busà et al. (2001). The latter paper also describes the atomic models for hydrogen and calcium adopted here.

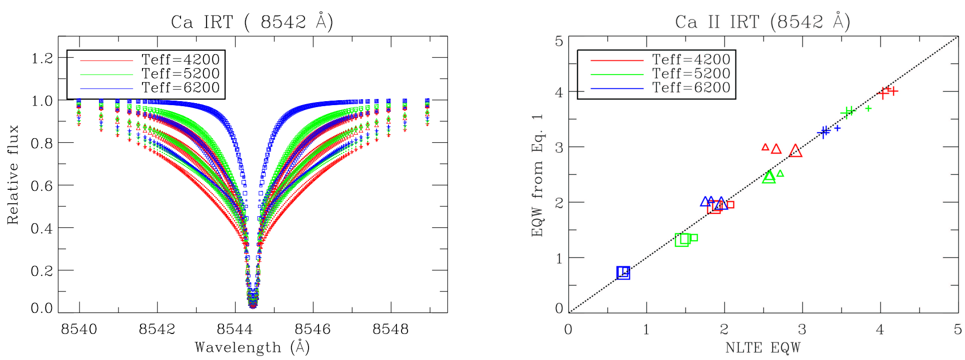

Figure 1. Computed line profiles (*left panel*) and comparison of computed NLTE EQWs with values approximated by Eq. 1 (*right panel*). Squares, triangles and crosses represent [A/H]=-2.0,-1.0 and 0.0 respectively. For each color and symbol, the models with $\log g$= 4.0, 4.5 and 5.0 are indicated, with large, medium and small size symbols respectively.

Fig. 1 shows the behavior of the Ca II IRT λ8542 Å line profile with changes in [A/H], $\log g$ and $T_{\rm eff}$. The sensitivity of the profile to metallicity is quite strong, expecially for the hottest models. The dependence on $T_{\rm eff}$ is evident only for metal-poor models, while the profiles change only slightly with $\log g$.

The measured EQWs (EQuivalent Widths) of the above profiles is well correlated with the stellar parameters. A multilinear fitting relation is in fact obtained with correlation coefficient of 0.99:

$$\begin{aligned} \mathrm{EQW(NLTE)} = a \times T_{\rm eff} + b \times \log g + c \times [\mathrm{A/H}] + d \times [\mathrm{A/H}] \times T_{\rm eff} + \\ + e \times [\mathrm{A/H}] \times \log g + f, \end{aligned} \quad (1)$$

where $a = -3.55 \times 10^{-4}$, $b = 8.3 \times 10^{-2}$, $c = 4.41 \times 10^{-1}$, $d = 1.20 \times 10^{-4}$, $e = 2.04 \times 10^{-2}$ and f=5.12. The strong dependence of EQWs on metallicity is evident from the relation. A comparison of the EQWs computed with Eq. 1 and actual calculated NLTE values is shown in the right-hand panel of Fig. 1.

3. Departure from LTE

Departure from LTE for the $\lambda8542$ Å line is shown in Fig. 2.

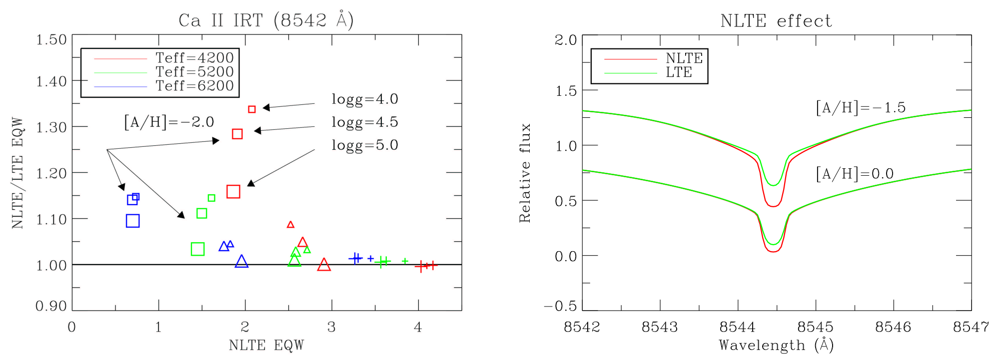

Figure 2. Departure from LTE for the $\lambda8542$ Å line. *Left panel:* EQW departures for all the models (symbols are the same as in Fig. 1); *Right panel:* NLTE effect in models with $\log g$=4.5 and $T_{\rm eff}$=5400 (upper profiles) and 5000 K (lower profiles)

The LTE departure of the EQW mainly depends on metallicity: it is below 10% when solar or -1.0 [A/H] models are considered, while it strongly increases, up to 35%, for [A/H]=-2.0 models. The sensitivity to $\log g$ and $T_{\rm eff}$ is quite strong only in low metallicity stars.

NLTE effects on the Ca II IRT line $\lambda8542$ Å profiles mainly affect the line core: we find that, even in models where the EQW departure from LTE is negligible the difference between LTE and NLTE is readily apparent in the core (see Fig. 2, right panel).

It is thus clear that a proper analysis of the Ca II IRT profiles, and sometimes even of the EQWs, requires a NLTE approach. The need for a NLTE treatment of Ca II IRT line formation is even stronger when investigating the diagnostic power of the CD (Central Depression) as an activity indicator.

4. Central Line Depression: An Activity Indicator?

Chmielewski (2000) analyzed the behavior of the CD($\lambda8542$) line in a sample of 40 stars. The author finds a correlation between the observed CD and the pure chromospheric indicator $\log R'_{\rm HK}$. The data and the fit relation he finds are shown in Fig. 3. However, as the author stresses, the observed CD cannot be considered a pure chromospheric indicator because no correction for the photospheric contribution is done.

In order to extract the chromospheric contribution to the observed CD of the line, we analyzed the behavior of the expected photospheric NLTE CD as function of the stellar parameters.

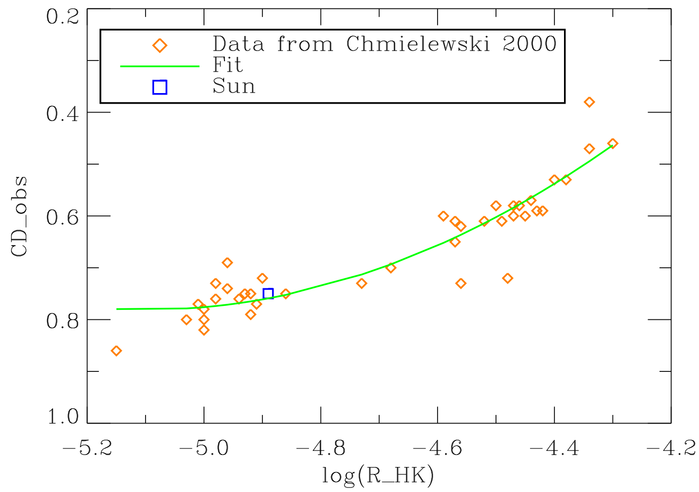

Figure 3. CD(λ8542) observational data and the fit relation from Chmielewski 2000; the data point corresponding to the Sun has been emphasized with square symbol.

We interpolated the calculated CD of the λ8542 Å line computed for the model grid with a multilinear function of stellar parameters; the resulting approximate relation is:

$$\mathrm{CD(NLTE)} = a \times T_{\mathrm{eff}} + b \times \log g + c \times [\mathrm{A/H}] + d \times [\mathrm{A/H}] \times T_{\mathrm{eff}} + \\ + e \times [\mathrm{A/H}] \times \log g + f, \quad (2)$$

where $a = 9.7 \times 10^{-8}$, $b = -1.12 \times 10^{-2}$, $c = -5.9 \times 10^{-2}$,$d = 7.3e \times 10^{-6}$, $e = 7.7 \times 10^{-3}$ and f=1.02, with a multilinear correlation coefficient of 0.93 (Fig. 4, left panel).

Eq. 2 indicates a very weak dependence of CD on stellar parameters: the calculated CD values span a rather narrow range, from 0.90 up to 0.98. Therefore, we expect that, being the dependence on stellar parameters so weak, $v \sin \hat{\imath}$ should dominate the observed CD in stars.

To take this into account, for each model of the grid we considered 8 $v \sin \hat{\imath}$ values spanning the range 2 km s^{-1} to 16 km s^{-1}(typical $v \sin \hat{\imath}$ values of the stars analyzed by Chmielewski 2000), looking for an expression of the rotation-convolved $\mathrm{CD_{conv}}$ in terms of T_{eff}, [A/H], $\log g$ and $v \sin \hat{\imath}$. We found that a quadratic dependence on $v \sin \hat{\imath}$, together with a multilinear function of the other parameters, interpolates the computed $\mathrm{CD_{conv}}$ quite well:

$$\mathrm{CD_{conv}(NLTE)} = A \times (v \sin \hat{\imath})^2 + a \times T_{\mathrm{eff}} + b \times \log g + c \times [\mathrm{A/H}] + \\ + d \times [\mathrm{A/H}] \times T_{\mathrm{eff}} + e \times [\mathrm{A/H}] \times \log g + f, \quad (3)$$

where $A = -9.0 \times 10^{-4}$, $a = -3.67 \times 10^{-6}$, $b = -2.91 \times 10^{-2}$,$c = -7.78 \times 10^{-2}$, $d = 1.77 \times 10^{-5}$, $e = 4.44 \times 10^{-3}$ and $f = 1.11$; the correlation coefficient for this approximation is $r = 0.95$ (Fig. 4, right panel).

5. A Better Activity Indicator: $R_{\rm IRT}$

Given the results described in the previous section, it is natural to consider as a better estimator of the chromospheric contribution to the Ca II IRT, for a star of known $T_{\rm eff}$, $\log g$, [A/H] and $v \sin \hat{\imath}$, the index given by the difference between the observed CD and $\mathrm{CD_{conv}}$(NLTE):

$$R_{\rm IRT} \equiv \mathrm{CD_{conv}(NLTE)} - \mathrm{CD_{obs}}. \qquad (4)$$

In the above equation, the value of $\mathrm{CD_{conv}}$(NLTE) can be either computed explicitly from a model photosphere of the star, or interpolated by using Eq. 3.

Fig. 5 shows, for the subset of stars considered by Chmielewski (2000) with known $v \sin \hat{\imath}$, the behavior of the index $R_{\rm IRT}$ versus $\log R'_{\rm HK}$.

The data points show a scatter significantly higher than that could be introduced by the use of the approximation of Eq. 3, as it can be expected from a non-homogeneous sample of observations (different instrumental resolution is not taken into account in Eq. 3), and because of errors in stellar parameters (mainly $v \sin \hat{\imath}$) and $\log R'_{\rm HK}$ measurements. Nevertheless, a correlation is clearly seen.

Best cubic and linear fits give, respectively:

$$\begin{aligned} y &= 1.94033 \times x^3 + 27.3210 \times x^2 + 128.289 \times x + 201.13 \qquad (5) \\ y &= 0.269 \times x + 1.49, \end{aligned}$$

where x=$\log R'_{\rm HK}$ and y=$R_{\rm IRT}$. Compared with the linear fit, the χ^2 of the cubic fit is somewhat better (by about 30%). Indeed, a flatter dependence on $\log R'_{\rm HK}$ can perhaps be seen at intermediate levels of activity (-4.5 < $\log R'_{\rm HK}$ < -4.9). It is worth noting that the Sun falls very near to the fitted relations.

A larger and more homogeneous sample of stars is needed to assess more precisely the relationship of $R_{\rm IRT}$ with $\log R'_{\rm HK}$ and with other activity indexes, but if this trend is confirmed, the $R_{\rm IRT}$ can be considered a good diagnostic of chromospheric activity only for either particularly active, or rather quiescent stars.

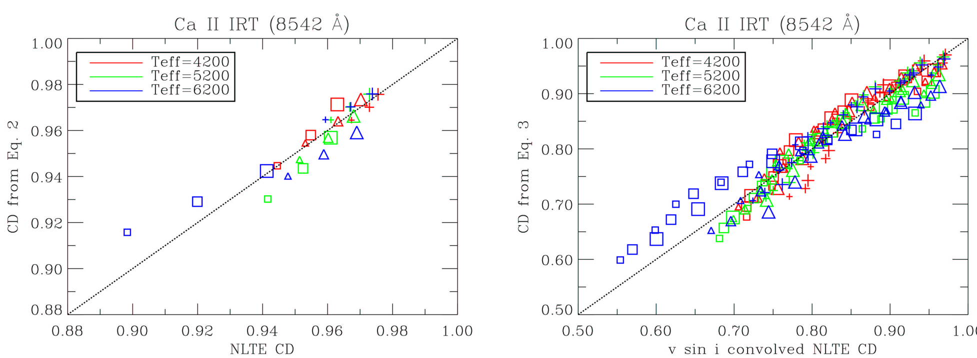

Figure 4. Predicted CD values from Eq. 2 (*left panel*) and from Eq. 3 (*right panel*) versus NLTE calculated CD. Symbols are the same as in Fig. 1.

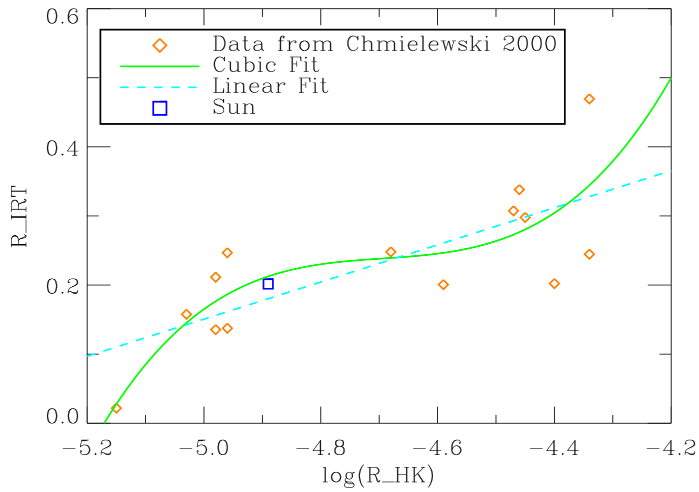

Figure 5. $R_{\rm IRT}$ versus $\log R'_{\rm HK}$ for the stars with known $v \sin \hat{\imath}$ of Chmielewski (2000).

6. Conclusions

The interpretation of Ca II IRT lines, even if restricted to the purely photospheric contribution, requires a NLTE analysis, unless EQWs only are considered, and only in stars with [A/H] > -1.0.

The line CD is less dependent than EQW on the photospheric parameters. However, a residual dependence is still present, which must be taken into account when correlating with other chromospheric activity indicators.

We found, however, that CD is not a good proxy for chromospheric activity. We therefore defined a new index, the observed CD relative to the photospheric value (computed in NLTE and concolved for $v \sin \hat{\imath}$): $R_{\rm IRT}$. We found that this purely chromospheric index is a good probe for stellar activity, at least in some ranges of activity levels.

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