Analysis of Potassium Abundance in a Large Number of Flares

J. Sylwester,[a] B. Sylwester,[a] K. J. H. Phillips,[b] J. L. Culhane,[c] C. Brown,[d] J. Lang[e] and A. I. Stepanov[f]

[a]*Space Research Centre, Polish Academy of Sciences, 51-622, Kopernika 11, Wrocław, Poland*

[b]*National Research Council Senior Research Associate, NASA Goddard Space Flight Center, Greenbelt, MD 20771, U.S.A.*

[c]*Mullard Space Science Laboratory, Holmbury St Mary, Dorking, Surrey RH5 6NT, United Kingdom*

[d]*E. O. Hulburt Center for Space Research, Naval Research Laboratory, Washington, D.C. 20375, U.S.A.*

[e]*Space Science Dept., Rutherford Appleton Laboratory, Didcot, Oxon. OX11 0QX, United Kingdom*

[f]*IZMIRAN, Russian Academy of Sciences, 142190, Troitsk, Moscow Region, Russia*

Abstract

An initial study of spectra observed in the shortest wavelength channel (3.40 Å-3.80 Å) of the RESIK X-ray spectrometer on *CORONAS-F* indicates the presence of substantial flare-to-flare variations in the line-to-continuum ratio of several lines, in particular He-like potassium (K XVIII) lines, occurring in the range 3.53 Å - 3.57 Å. The observed variations are larger than those expected from temperature variations. This has motivated a study of possible variations in the potassium abundance in the observed spectra. With a new RESIK calibration available, we have obtained absolute fluxes of the K XVIII resonance line as well as the continuum and lines observed in other RESIK channels (3.40 Å - 6.05 Å) for some 1163 intervals observed early in 2003. Analysis of these observations allowed us to determine the average absolute potassium abundance for the period studied and investigate the variability of abundance. The results obtained are presented and discussed.

Key words: Sun, X-ray, spectra, abundance, potassium

Preprint submitted to Elsevier Science *15 April 2005*

1 Introduction

This paper is concerned with the observation of He-like potassium (K XVIII) lines in coronal X-ray spectra made with the RESIK (REntgenowsky Spektrometr s Izognutymi Kristalami) Bragg bent crystal spectrometer on the Russian spacecraft *CORONAS-F* (J. Sylwester et al. 2004). *CORONAS-F* was launched on 2001 July 31, and continues to operate till the present time. Between the time of launch and 2003 May, RESIK obtained spectra in the wavelength range 3.40 Å - 6.05 Å for active regions and during the course of many solar flares. He-like potassium produces a triplet of lines, known (after Gabriel 1972) as the resonance line ($1s^2\,{}^1S_0 - 1s2p\,{}^1P_1$, also called w, at 3.532 Å), intercombination lines (a blend of $1s^2\,{}^1S_0 - 1s2p\,{}^3P_2$ or x and $1s^2\,{}^1S_0 - 1s2p\,{}^3P_1$ or y, at 3.55 Å), and forbidden line ($1s^2\,{}^1S_0 - 1s2p\,{}^3P_2$ or z, at 3.571 Å).

The lines occur in RESIK channel 1 (wavelength range: 3.40 Å - 3.80 Å), and are generally weak, though their strength increases with plasma temperature (J. Sylwester et al. 2002). Unlike most crystal spectrometers operating in the soft X-ray range, RESIK observes the continuum uncontaminated by instrumental background in channels 1 and 2 (3.40 Å - 4.27 Å), while for channels 3 and 4, an instrumental background formed by fluorescence of the crystals by solar X-rays can be subtracted with routines written by the RESIK instrument team. Reduced spectra are therefore ideal for obtaining values of the absolute abundance of elements observed by RESIK, particularly potassium which is of interest in discussions of solar atmospheric abundances. This is because of the low value (4.34 eV) of its first ionization potential (FIP). It is generally belived that FIP is a parameter convenient for describing difference of the coronal and photospheric abundances. Abundances of low FIP elements (FIP $<$ 10 eV), are deduced to be substantially greater in the corona than in the photosphere (Feldman 1992).

A companion paper (B. Sylwester et al. 2004) has described the selection of all 1163 time-contiguous spectra observations for a wide variety of solar activity occurring between 2003 January 1 and March 14. The spectra integration times have been varying from fraction of a minute to $\sim$20 min for this set. These observations have been used to obtain values of the potassium line fluxes, and the variation of these fluxes with temperature studied. We report here an averaged value for the flare abundance of potassium as well as evidence of variations in the potassium abundance.

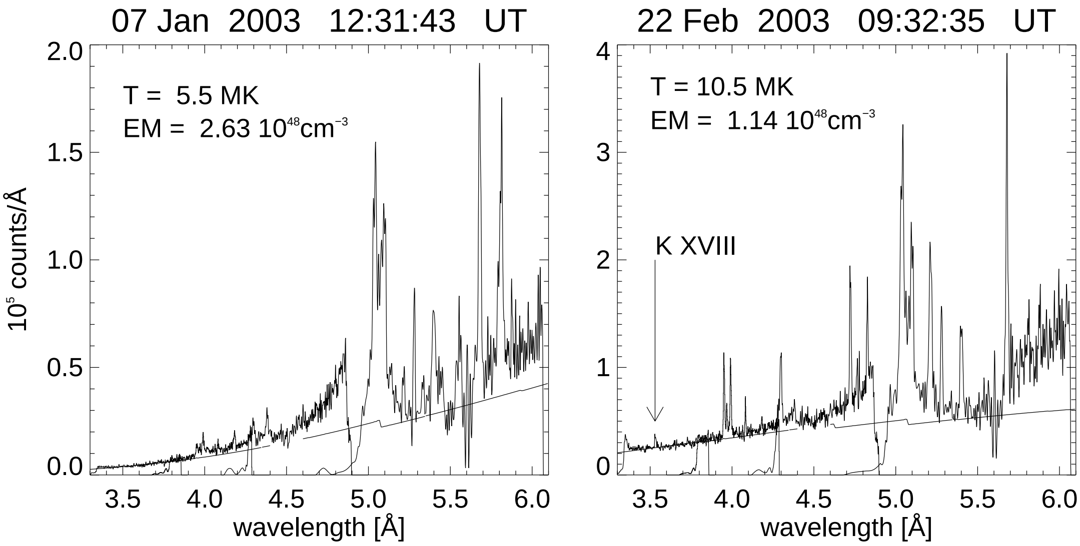

Fig. 1. Examples of spectra from the set of 1163 events representative of cooler (left) and hotter plasma conditions. The temperatures and emission measures as derived from ratios of flux in channels 1 and 4 are shown, as is the corresponding continuum (thin line).

2 Observations and Analysis

The 1163 spectra obtained by B. Sylwester et al. (2004) were analyzed by finding the ratio of the total flux in channel 1 (3.40 Å - 3.80 Å) to the total flux in channel 4 (5.00 Å - 6.05 Å), the two channels with the widest energy separation. Theoretical spectra from the CHIANTI atomic code and database were used to get values of temperature T and emission measure EM on an isothermal assumption. Figure 1 shows, for all four RESIK channels, example spectra having widely different temperatures (5.5 MK and 10.5 MK respectively). The lines due to K XVIII are evident only in the higher-temperature spectrum. The other principal lines are identified in a companion work by B. Sylwester et al. (2004) in these Proceedings. The continuum (sum of free–free and free-bound emission) as calculated from CHIANTI is shown in each plot, based on the derived values of temperature and emission measure. Departures of the observed background and this continuum are currently under investigation; they are only significant for channel 4 (cf. Fig. 2).

Figure 2 (left panel) shows the spectral region around the K XVIII lines for all spectra summed. The complete triplet of lines ($w - z$) is apparent and well resolved, as is the dielectronic satellite line k emitted by Li-like K (K XVII, formed by the dielectronic recombination of He-like K). Other K XVII dielectronic satellites, in particular j, are blended with K XVIII lines. This figure also shows the wavelength limits, 3.528 Å - 3.538 Å, which were used to define the value of the flux of the K XVIII w line (with the continuum contribution removed) for all the spectra analyzed. Figure 2 (right panel) shows these values of the w line flux divided by the emission measure and (for convenience of display) multiplied by a factor 10^{44}, plotted against temperature. A definite trend with temperature is clearly visible. The solid curve is a third-order polynomial fit to the data. The observed trend is apparently mostly attributable to the variation with T of the emission function $G(T)$ of the w line. This is illustrated by the theoretical $G(T)$ function, obtained by interpolation of emission functions of the He-like argon and calcium w lines, used in a previous analysis (Phillips et al., 2003). The departure of the observed points in Figure 2 (right panel) at low temperatures ($\lesssim$ 8 MK) may be attributed to the presence of unresolved, high-n, dielectronic K XVII satellites which (like the resolved $n = 2$ satellite j) have an approximately T^{-1} temperature dependence.

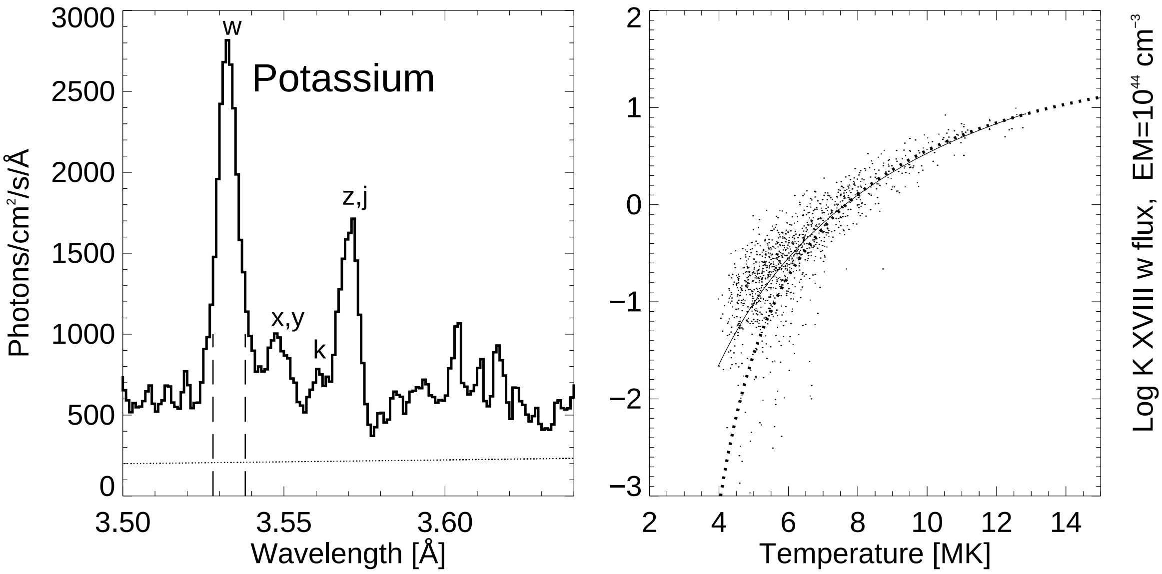

Fig. 2. *Left*: Average spectrum in vicinity of potassium triplet as obtained by summing over $\sim$ 400 hours of spectral measurements. The dashed vertical lines are those chosen to include the emission of the K XVIII w line. *Right*: The observed values (points) of w line flux, divided by the emission measure and multiplied by a factor 10^{44}, plotted against temperature. Thin line represents best cubic fit to these points while the thick dotted line is the theoretically predicted variation for the average value $A_{\rm Kav} = 6.00 \times 10^{-7}$, four times the photospheric one.

There are many points in this plot which depart by up to a factor of 4 from the main trend, some larger, others smaller. The distribution of the deviation from the main trend is illustrated in more details in Figure 3. In this plot, the abundance determinations are shown as a scatter plot, with the temperature on the horizontal axis. On the (logarithmic) vertical axis difference of the observed potassium abundance from a zero level is displayed. The zero level corresponds to $A_{\rm Kav} = 6.00 \times 10^{-7}$, i.e. a coronal value, four times the photospheric value of Takeda et al. (1996). It can be seen that an overwhelming number of points are within a factor of 2 of the average (cf. thin lines in Figure 3), but most of them are above the photospheric level. Note that the overall width of the scatter distribution in Figure 3 (right panel) is much larger than the width of particular uncertainty of any individual measurement. A trend is observed that the abundance scatter is larger for weaker flares. This trend appears to be of physical origin rather than due to measurement uncertainties. The differences of the event-to-event potassium abundance are so significant that they can be seen just by inspection of the spectra by eye. Figure 4 shows two

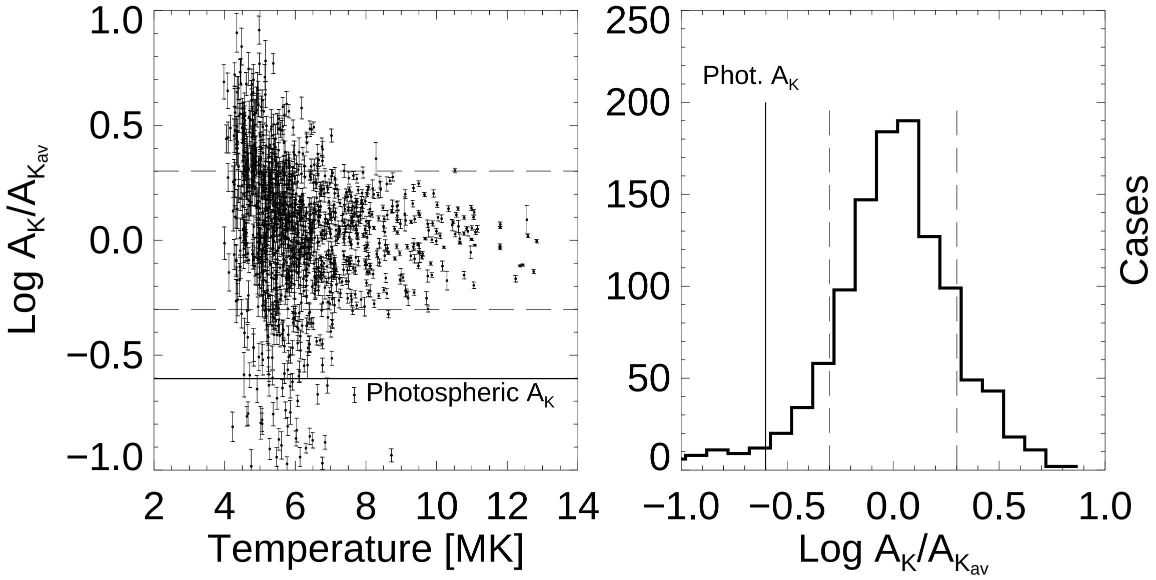

Fig. 3. *Left*: Difference plot of the observed and fitted average temperature dependence of the K XVIII w line flux. The scatter is largest for lower temperatures and is much larger than individual measurement 1σ uncertainties. This is interpreted as being due to event-to-event differences in potassium abundance. *Right*: Histogram of the scatter with the value of the photospheric K abundance indicated.

summed spectra, taken on eight occasions, when the K XVIII lines were more intense than the broad trend and when the lines were hardly visible. There are two possible reasons for these departures. The first is that the isothermal approximation taken in this analysis is not completely valid, i.e. the presence of a higher-temperature component raises the K XVIII line intensities without much affecting the ratio of the total emission in channels 1 and 4. This does not seem to be a large contributing factor, however, since the channel 1 flux is dominated by continuum being formed at temperatures even higher than the K XVIII line itself. The second possible interpretation of the scatter of the observed points from the average trend line is that there are event-to-event variations of approximately a factor of 4 in the abundance of potassium, as previously pointed out by Sylwester et al. (1997) for calcium. Such variations might be expected if the FIP effect operates in a different way for some flares, for the general corona and/or for active regions. We are currently investigating the correlation of the times of these spectra with occurrence of hard X-ray emission (indicating the presence of nonthermal electrons) and other factors which may contribute to the observed variability.

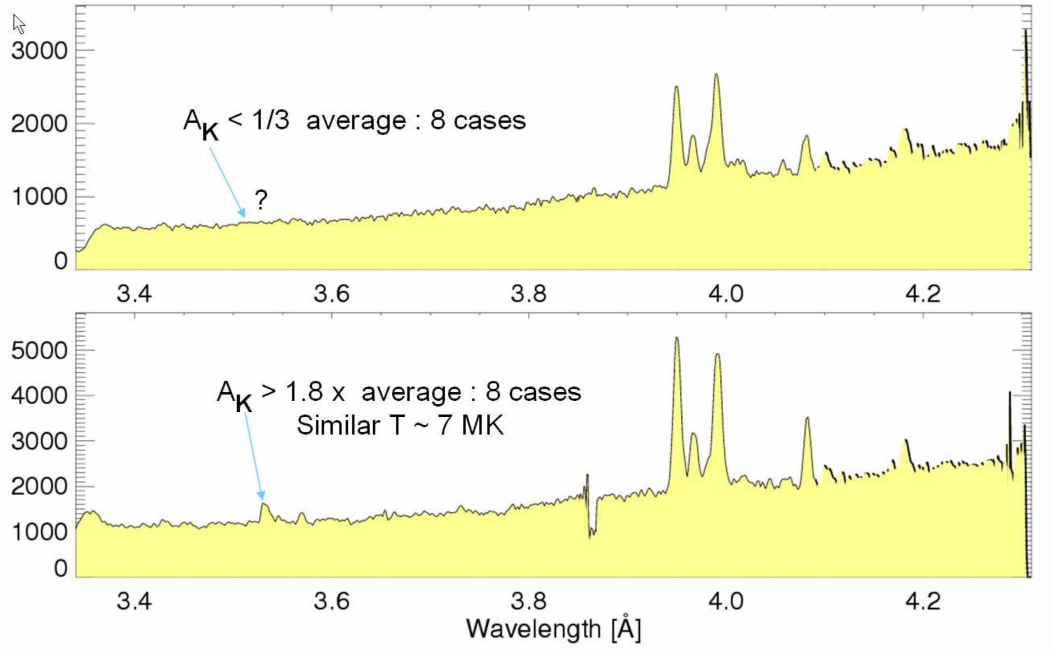

Fig. 4. Examples of the RESIK spectra averaged for times when the K XVIII lines are barely visible (upper) and rather prominent. Temperature variability is unlikely to account for the differences observed, so it appears that corresponding plasma composition differs in potassium abundance.

3 Summary and Conclusions

We have analyzed 1163 spectra to derive the temperature behaviour of the intensity of the K XVIII w X-ray line at 3.53 Å. Dividing the flux of this line by the emission measure at the time of each observation gives a dependence on temperature with its value known from the ratio of total flux in RESIK channels 1 and 4. The observations are in agreement with the theoretical emissivity function for this line, allowing for the presence of unresolved dielectronic satellites, and assuming a coronal abundance of potassium, i.e. four times the photospheric abundance. There are some departures from the curve of more than a factor of $\sim$4. This may be because, for such spectra, an isothermal approximation is an inadequate description, with higher-temperature components possibly giving rise to increased intensity of the w line, though this is unlikely as the temperature complexity of the contributing source would inevitably influence channel 1 total flux even more. Another more acceptable possibility is that there are event-to-event variations in the abundance of potassium (see discussion of similar abundance variations for calcium, J. Sylwester at al. 1997). Investigations of such variations may reveal the mechanism of FIP effect in coronal plasmas.

Acknowledgements

B.S. and J.S. acknowledge support from grants 2.P03D.002.22 and BPZ-KBN-054/P03/2001 of the Polish Committee for Scientific Research. K.J.H.P. acknowledges support from the U.S. National Research Council Research Associateship Program.

References

Feldman, U., 1992, Elemental Abundances in the Upper Solar Atmosphere, *Physica Scripta*, 46, 202.

Gabriel, A. H., 1972, Dielectronic satellite spectra for highly-charged helium-like ion lines, *M.N.R.A.S.*, 160, 99.

Phillips, K. J. H., Sylwester, J., Sylwester, B., & Landi, E., 2003, Solar Flare Abundances of Potassium, Argon, and Sulphur, *ApJ*, 589, L113.

Sylwester, J., Lemen, J. R., Bentley, R. D., Fludra, A. & , Zolcinski, M.-C., 1997, Detailed Evidence For Flare-To-Flare Variations of the Coronal Calcium Abundance, *ApJ*, 501, 397-407.

Sylwester, B., Sylwester, J., Siarkowski, M., Phillips, K. J. H., Culhane, J. L., Lang, J., Brown, C., & Kuznetsov, V. D., 2004, Identification of Lines in the Range 3.35 Å – 6.1 Å Observed in RESIK Spectra, Paper E1.9-0032-04, *These Proceedings*.

Sylwester, J., Culhane, J. L., Doschek, G. A., Oraevsky, V. N., Phillips, K. J. H., & Sylwester, B., 2002, RESIK observations of highly ionized argon and potassium X-ray emission lines in solar flares, Proc. Tenth European Solar Physics Meeting, Prague: *ESA SP-506*, 765.

Sylwester, J. et al., 2004, RESIK: A Bent Crystal X-ray Spectrometer for Studies of Solar Coronal Plasma Composition, *Solar Phys.* (accepted).

Takeda, Y. Kato, K., Watanabe, Y., & Sadakane, K., 1996, Line Profile Analysis of K I 7699 in the Sun and Procyon, *Publ. Astro. Soc. Japan*, 48, 511-528.