Available online at www.sciencedirect.com
ScienceDirect
Advances in Space Research 42 (2008) 833–837
ADVANCES IN SPACE RESEARCH
(a COSPAR publication)
www.elsevier.com/locate/asr

He-like Ar XVII triplet observed by RESIK

B. Sylwester [a,*], J. Sylwester [a], K.J.H. Phillips [b], E. Landi [c]

[a] Space Research Centre, Polish Academy of Sciences, ul. Kopernika 11, PL-51-622 Wroclaw, Poland
[b] Mullard Space Science Laboratory, University College London, Holmbury St. Mary, Dorking, Surrey, UK
[c] Artep, Inc., Naval Research Laboratory, USA

Received 3 November 2006; received in revised form 5 April 2007; accepted 18 April 2007

Abstract

We present the observations of He-like Ar triplet lines obtained by RESIK spectrometer aboard *CORONAS-F*. Interpretation of intensity ratios between triplet lines of lower Z elements is known to provide useful diagnostics of plasma conditions within the emitting source. Here, we investigate whether triplet line ratios are useful for interpretation of higher Z element spectra. A high sensitivity, low background and precise absolute calibration of RESIK allow to consider in addition also the continuum contribution. This provides a way to determine the Ar absolute abundance from the observed triplet component ratios. The method is presented and the results are shown for two selected flares. Derived values of Ar absolute abundance for these flares are found to be similar: 2.6×10^{-6} and 2.9×10^{-6}. They fall in the range between presently accepted Ar photospheric and coronal abundances.

Keywords: Solar physics; X-ray flares; Spectroscopic plasma diagnostic

1. Introduction

The RESIK instrument, a part of the Russian satellite *CORONAS-F*, consists of two double-channel X-ray spectrometers, designed to observe hotter solar plasmas. The detailed description of the instrument, including its operation and calibration, is available in the paper by Sylwester et al. (2005). The nominal wavelength coverage of RESIK is 3.35–6.1 Å in four wavelength channels. The spectra observed in this range contain several spectral features useful for the X-ray plasma diagnostics. The observed line intensities can be used in order to study the physical conditions in the flaring plasma as has been shown by Phillips et al. (2006a,b). RESIK spectra allow also to investigate the coronal plasma composition (Phillips et al., 2003). In the RESIK spectra, one can find lines belonging to the elements with substantially different values of FIP (First Ionization Potential), from K with FIP = 4.34 eV through S with FIP = 10.36 eV to Ar with FIP = 15.75 eV, which will make it possible to study the so-called FIP effect. The identification of basic lines present on RESIK spectra is given in the papers: Sylwester et al. (2003, 2006a) and Kepa et al. (2006). Among many lines seen in the RESIK spectra, the He-like triplets of K XVIII, Ar XVII, Cl XVI and S XV ions "stand out". They are observed in the following wavelength bands: 3.52–3.58, 3.93–4.005, 4.44–4.50 and 4.953–5.15 Å, respectively, and they are the subject of our present interest.

2. The analysis

Fig. 1 shows the entire RESIK spectrum integrated over all available spectral measurements of the 2003 January 7 (23:30 UT) flare. The integration time covers 49% of the whole event duration. The flare seen on the limb was of M4.9 *GOES* class, and lasted for 2 h. The satellite nights and/or radiation zones transits prevented the spectra from being collected over these times. The rise and late decay phases of this flare were, however, well covered by the

* Corresponding author.
E-mail address: bs@cbk.pan.wroc.pl (B. Sylwester).

0273-1177/$34.00 © 2008 Published by Elsevier Ltd on behalf of COSPAR.
doi:10.1016/j.asr.2007.04.060

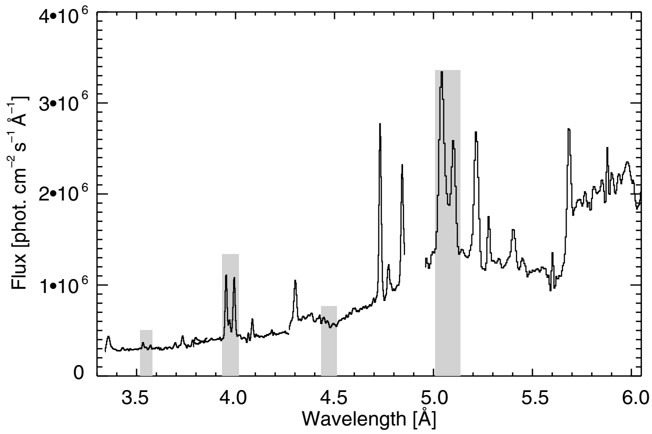

Fig. 1. Calibrated RESIK spectrum of the 2003 January 7 (at 23:30 UT) flare integrated over 3090 s (units are absolute fluxes at Earth). The orbital background has been subtracted. The four spectral bands marked in grey tone include the He-like triplets of K, Ar, Cl and S.

observations; the early decay was covered only partly and the maximum phase and part of decay was not observed by RESIK. The time coverage is seen in Fig. 2 where the total fluxes of X-ray emission collected in the four spectral bands marked in Fig. 1 are shown. At the top and bottom of the Figure, two light curves are presented for the comparison: *GOES* (1–8 Å), and *RHESSI* (25–50 keV). In the middle the fluxes observed by RESIK in vicinity of the He-like triplets are shown. An arbitrary scale has been used on the vertical axis in order to bring to the common scale variability of the fluxes measured by different instruments and expressed in different units. The term triplet describes a group of lines which consists of the three most intense spectral components formed in He-like ions. These lines correspond to the transitions between $n = 2$ and the $n = 1$ (ground-state) shells. They are: the resonance (w after Gabriel and Jordan (1969): $1s^2\ ^1S_0$–$1s2p\ ^1P_1$), the unresolved intercombination lines ($x + y$: $1s^2\ ^1S_0$–$1s2p\ ^3P_{1,2}$) and the forbidden (z: $1s^2\ ^1S_0$–$1s2s\ ^3S_1$). Gabriel and Jordan (1969) recognized that the ratios of these lines could provide important plasma diagnostics for electron density N_e and temperature T_e. The following two ratios have been found the most useful:

$$R(N_e, T_e) = \frac{f_z}{f_{x+y}} \quad \text{and} \quad G(T_e) = \frac{(f_z + f_{x+y})}{f_w} \tag{1}$$

Here f_w, f_{x+y} and f_z denote the fluxes in the resonance, intercombination and forbidden lines, respectively. It is known from theoretical considerations that in the case of triplets observed by RESIK i.e. for a higher Z elements, we can not expect any dependence of R ratio on the density, since for typical solar plasma conditions, R is always expected to be close to the so-called low density limit. However, we may attempt to use the G ratio for the temperature analysis. Within the spectral range covered by RESIK there are many pairs of lines which ratios are sensitive to the plasma temperature. Some of them have been explored already in the papers by Phillips et al. (2006a,b) and Sylwester et al. (2006b). The multitemperature analysis (where a distribution of plasma with the temperature is allowed) can be performed based on the lines observed by RESIK and this was done by Kepa et al. (2004, 2006). However, for studies of the lines and continuum being formed in a similar temperature range, like in case of the He-like triplets, a simple isothermal approximation, often used in the literature is sufficient. In this research, we decided to use the observed band G ratios for studies of the flaring plasma properties in preparation for a subsequent analysis of the role of FIP effect. As can be seen in Fig. 1, the most favorable for the analysis is the Ar XVII triplet at the 3.93–4.005 Å range as it has strong, well resolved spectral components as well as sufficiently strong continuum observed. This allows to study respective bands'

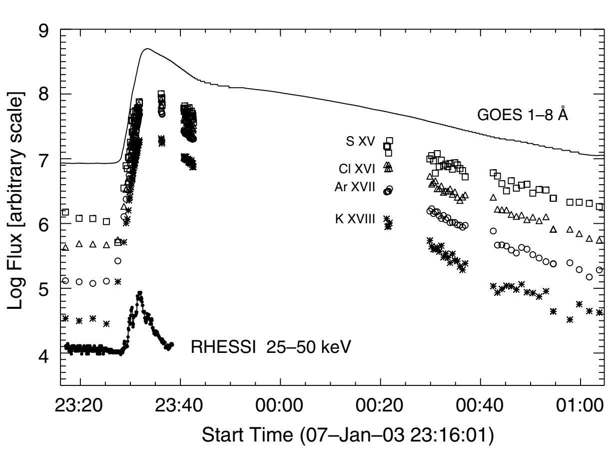

Fig. 2. The X-ray light curves of 2003 January 7 flare. The *GOES* and *RHESSI* data are presented for comparison at the top and the bottom of the Figure. The total fluxes in the bands that include the He-like triplets are indicated with respective symbols (squares, triangles, circles, and stars for K XVIII, Ar XVII, Cl XVI and S XV ions). Plotted fluxes include combined contribution of the lines and the continuum within each selected spectral band.

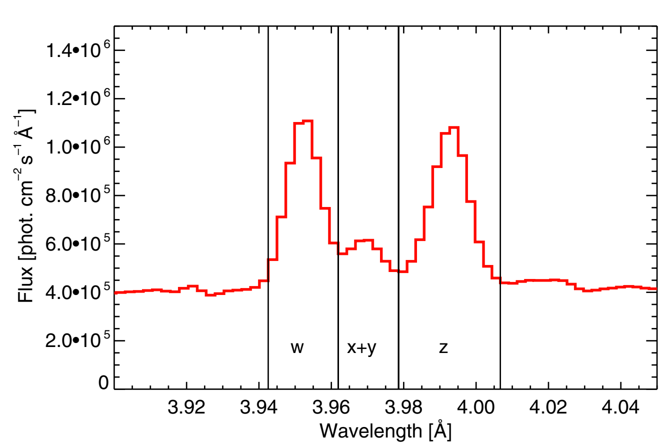

Fig. 3. A part of the average spectrum of 2003 January 7 flare covering the vicinity of the Ar XVII He-like triplet. The three analyzed spectral bands are marked (w, $x + y$ and z). These bands include the resonance, intercombination and forbidden principal triplet lines as well as the continuum, the lines are standing atop.

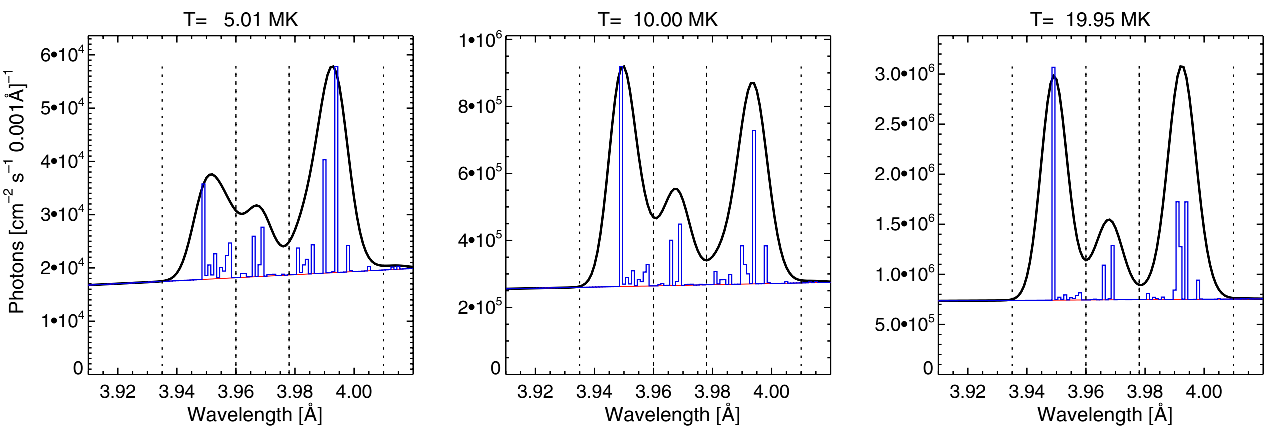

Fig. 4. The synthetic spectra in the vicinity of Ar XVII triplet calculated for three selected temperatures based on CHIANTI v5.2 code. The individual lines (as well of Ar as of the other elements contributing to the analyzed range) have been convolved with the RESIK instrumental profile. The thick line represents the total predicted spectral shape while the vertical bars indicate positions and the relative strengths of stronger lines.

behavior as well for low as for high activity levels. The K XVIII and Cl XVI triplets are of much lower intensity due to a small K and Cl solar abundances. The determination of chlorine abundance based on RESIK spectra has been presented in the paper by Sylwester et al. (2004). The S XV triplet is also intense, but the spectra are of much lower resolution and the intercombination line cannot be resolved. Therefore, for illustration of the method used here for the abundance analysis, we have selected the Ar XVII triplet. In Fig. 3, we present respective average spectrum as observed by RESIK for the flare on 2003 January 7 at 23:30 UT. We have indicated the three bands (called w, $x+y$ and z according to the notation of the most prominent lines in these regions) covering the wavelengths: 3.942–3.961, 3.961–3.978 and 3.978–4.006 Å, respectively. The fluxes observed in these three bands were used further on in the analysis. We have calculated the corresponding theoretical spectra in these bands using the CHIANTI v5.2 code (Dere et al., 1997) and assuming various plasma temperatures and elemental abundances. In the calculations, we have taken into account the contribution of all the lines and the continuum contributing to the selected bands. Examples of such spectral synthesis calculations for three selected temperatures namely 5, 10 and 20 MK and assumed coronal plasma composition from the paper by Feldman and Laming (2000) are shown in Fig. 4. The dashed vertical lines correspond to our sub-band division. This exact division corresponds to the bin edges in the observed spectra which depends somewhat on the position of the flare on the solar disk. The solid vertical bars represent individual lines intensities and the thicker solid envelope is the shape of the spectrum as would be observed by RESIK (i.e. the theoretical intensities convolved with the instrumental profile). It is directly seen from this plot that a strong dependence of individual bands' intensities on the temperature is present. We have found it useful to construct the G ratios similar to that introduced by Gabriel and Jordan (1969) but with individual components containing *all the lines and the continuum* contribution to the given wavelength band. There is no

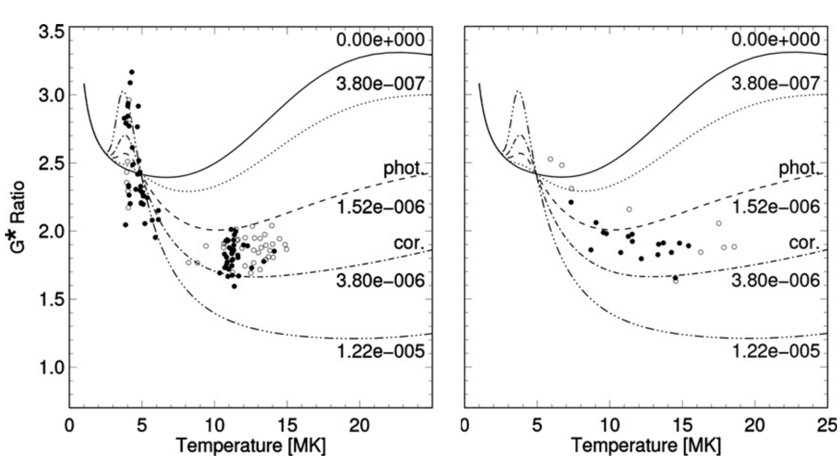

Fig. 5. The comparison of temperature behavior of theoretical G^* ratios as calculated for various assumed Ar abundances with RESIK observations for two flares. The numbers at the right indicate values of Ar abundances. Respective photospheric and coronal abundances are indicated. The left panel is for 2003 January 7 flare at 23:30 UT; the right panel is for a short-lived flare on 2003 February 22 at 09:30 UT. The open points correspond to the flare rise phases, while the filled points to the decay phases.

Table 1
Characteristics of analysed flares

Data	Maximum [UT]	Duration [min]	*GOES* class	Location
7 January 2003	23:33	100	M4.9	Limb
22 February 2003	09:29	12	C5.8	Centre

way how to *a priori* separate precisely the line and continuum contributions in the observed spectra. In accordance with, we have calculated the G^* ratios defined as:

$$G^*(T_e) = \frac{(f_w^* + f_{x+y}^*)}{f_z^*} \quad (2)$$

where the f_w^*, f_{x+y}^* and f_z^* denote the fluxes of *all lines and continuum* contributing to the selected wavelength range of the parent resonance, intercombination and forbidden lines, respectively. In the next step, we have calculated the grid of theoretical G^* ratios using the CHIANTI code. We have compared the observed values with corresponding theoretical plots obtained for a number of assumed Ar abundance values. In performing the CHIANTI spectral synthesis, we assumed the standard coronal abundance (Feldman and Laming, 2000) for all other elements except Ar. The results of this comparison are displayed in Fig. 5, where the theoretical lines are plotted for five chosen values of Ar abundance. The two of the theoretical curves (denoted as phot. and cor.) correspond to presently accepted photospheric $A_{\mathrm{Ar}} = 1.51 \times 10^{-6}$ and coronal $A_{\mathrm{Ar}} = 3.80 \times 10^{-6}$ Ar abundances: Asplund et al. (2005) and Feldman and Laming (2000), respectively. Inspection of these plots indicates that the G^* ratios are not the best way to determine the temperature as for some values of Ar abundances they provide non-unique solutions. If we adopt the coronal Ar abundance, from measured $G^* = 1.8$ one can not be sure which of the temperatures: 9 or 22 MK is realistic. So, in order to compare the theory with the observations, we have decided to use the average temperature characterizing the emitting plasma as obtained from the ratio of broad-band fluxes (RESIK channels Ch. 1: 3.37–3.88 Å and Ch. 4: 4.96–6.09 Å and *GOES*). As the reduced RESIK spectra are very well calibrated in absolute terms we are able to determine the corresponding observed G^* ratios quite precisely (10–30%). This has been done for all available spectra and the results for two flares (see Table 1 for their characteristics) are put atop the theoretical curves in Fig. 5. Left panel is for 2003 January 7 event and right panel is for a short duration flare on 2003 February 22. Being short, the entire flare was continuously covered by RESIK observations. The observed points have been overplotted on the theoretical curves using open circles for the rise phase and filled circles for the decay phase. It is seen from the Figure that for both flares the observed points are located mostly in between the curves corresponding to the photospheric and coronal Ar abundances. There is no clear difference between the rise and decay phase behavior. Derived average values of Ar abundances are 2.6×10^{-6} and 2.9×10^{-6} for 2003 January 7 and 2003 February 22 flares, respectively.

3. Concluding remarks

The RESIK observations constitute a unique spectral database for analysis of He-like triplets of K, Ar and Cl. In the present analysis, we concentrated on the interpretation of Ar triplet intensity ratios. We interpret in detail the spectral band fluxes including both the lines and the continuum radiation. We have shown that the so-called G^* ratio is sensitive to the elemental abundance of Ar. We introduce respective method of Ar abundance determination based on the analysis of spectral bands containing the He-like triplet. It is essential for the presented analysis that the considered band fluxes contain both spectral components: the line and the continuum contribution. The method is used to interpret the observations obtained for two solar flares, rather different in terms of class, duration and location. Derived absolute values of average Ar abundances for these events are similar: 2.6×10^{-6} and 2.9×10^{-6}, with the ±30% uncertainties. They fit between presently accepted values of absolute photospheric (1.51×10^{-6}) and coronal (3.80×10^{-6}) abundances. As argon belongs to a high FIP group of elements, one would expect the value of absolute abundance rather close to the photospheric one, in accordance with usual solar FIP effect. A more elaborated method of elemental abundances analysis is presented in the accompanying paper by Sylwester et al. (2008). This other method is based on exact fitting of the spectral shape within the observed small intervals. The abundances obtained there for Ar are in overall agreement with the present results.

Acknowledgements

RESIK is a common project between NRL (USA), MSSL and RAL (UK), IZMIRAN (Russia) and SRC (Poland). B.S and J.S. acknowledge support from the Polish Ministry of Education and Science Grant 1.P03D.017.29. We express our gratitude to unknown Referees of this contribution whose remarks improved the content.

References

Asplund, M., Grevesse, N., Sauval, A.J. Cosmic abundances as records of stellar evolution and nucleosynthesis. ASP Conf. Ser. 336, 25–38, 2005.

Dere, K.P., Landi, E., Mason, H.E.others An atomic database for emission lines. Astron. Astrophys. Suppl. 125, 149–173, 1997.

Feldman, U., Laming, J.M. Elemental abundances in the upper atmospheres of the Sun and stars: update of observational result. Phys. Scripta 61, 222–252, 2000.

Gabriel, A.H., Jordan, C. Interpretation of solar helium-like ion line intensities. Mon. Not. R. Astron . Soc. 145, 241–248, 1969.

Kepa, A., Sylwester, J., Sylwester, B., Siarkowski, M. First determinations of differential emission measure distribution based on RESIK X-ray spectra. Proc. IAU Symp. 223, 461–462, 2004.

Kepa, A., Sylwester, J., Sylwester, B., Siarkowski, M., Phillips, K.J.H., Kuznietsov, V.D. Observations of $1s^2$–$1s$ *np* and $1s$–*np* lines in RESIK soft X-ray spectra. Adv. Space Res. 38, 1534–1537, 2006.

Phillips, K.J.H., Sylwester, J., Sylwester, B., Landi, E. Solar flare abundances of potassium, argon, and sulphur. ApJ 589, L113–L116, 2003.

Phillips, K.J.H., Dubau, J., Sylwester, J., Sylwester, B., Culhane, J.L., Doschek, G.A., Lang, J. Temperature sensitive plasma diagnostics based on Si satellite-to-resonance line ratios for $1s^2$–$1snp$ transitions. Adv. Space Res. 38, 1543–1546, 2006a.

Phillips, K.J.H., Dubau, J., Sylwester, J., Sylwester, B. Si XII X-ray satellite lines in solar flare spectra. ApJ 638, 1154–1161, 2006b.

Sylwester, J., Sylwester, B., Culhane, J.L., Doschek, G.A., Oraevsky, V.N., Phillips, K.J.H. Patterns of X-ray line emission variability as observed by the RESIK Bragg spectrometer. ESA SP-535, 733–738, 2003.

Sylwester, B., Sylwester, J., Siarkowski, M., Phillips, K.J.H., Landi, E. Detection of H- and He-like resonance lines of chlorine in solar flare spectra. Proc. IAU Symp. 223, 671–672, 2004.

Sylwester, J., Gaicki, I., Kordylewski, Z., et al. RESIK: a bent crystal X-ray spectrometer for Studies of solar coronal plasma composition. Sol. Phys. 226, 45–72, 2005.

Sylwester, B., Sylwester, J., Siarkowski, M.5 others Lines in the range 3.2 Å–6.1 Å observed in RESIK spectra. Adv. Space Res. 38, 1490–1493, 2006a.

Sylwester, B., Sylwester, J., Kepa, A., Phillips, K.J.H. Determination of flaring plasma characteristics from RESIK X-ray Spectra. Proc. IAU Symp. 233, 165–168, 2006b.

Sylwester, J., Sylwester, B., Landi, E., Phillips, K.J.H., Kuznetsov, V.D. Determination of K, Ar, Cl, S and Si flare abundances from RESIK soft X-ray spectra. Adv. Space. Res. 42, 838–843, 2008.