THE X-RAY LINE FEATURE AT 3.5 KeV IN GALAXY CLUSTER SPECTRA

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ABSTRACT

Recent work by Bulbul et al. and Boyarsky et al. has suggested that a line feature at ~3.5 keV in the X-ray spectra of galaxy clusters and individual galaxies seen with XMM-Newton is due to the decay of sterile neutrinos, a dark matter candidate. This identification has been criticized by Jeltema & Profumo on the grounds that model spectra suggest that atomic transitions in helium-like potassium (K XVIII) and chlorine (Cl XVI) are more likely to be the emitters. Here it is pointed out that the K XVIII lines have been observed in numerous solar flare spectra at high spectral resolution with the RESIK crystal spectrometer and also appear in Chandra HETG spectra of the coronally active star σ Gem. In addition, the solar flare spectra at least indicate a mean coronal potassium abundance, which is a factor between 9 and 11 higher than the solar photospheric abundance. This fact, together with the low statistical quality of the XMM-Newton spectra, completely account for the ~3.5 keV feature and there is therefore no need to invoke a sterile neutrino interpretation of the observed line feature at ~3.5 keV.

Key words: galaxies: clusters – general – galaxies: individual (M31) – Sun: abundances – Sun: X-rays, gamma rays – X-rays: galaxies: clusters

1. INTRODUCTION

In recent analyses of X-ray spectra of galaxy clusters, the Milky Way center, and individual galaxies including M31, Bulbul et al. (2014a) and Boyarsky et al. (2014b) have claimed that an excess of emission over the range 3.47–3.51 keV (3.53–3.57 Å) is a signature of the decay of sterile neutrinos (a dark matter candidate). The possibility that this line emission is due to helium-like potassium (K XVIII) was investigated using the AtomDB (APEC) atomic code but was rejected on the grounds that the observed line feature is about a factor 20 more intense than the potassium lines assuming the solar photospheric K abundance. Unfortunately, these authors have neglected the fact that this region has been seen with high spectral resolution in numerous solar flare spectra with temperatures up to 22 MK (1.9 keV) using the RESIK crystal spectrometer (Sylwester et al. 2005, 2010b) and in the spectra of a binary star system with an active corona (σ Gem) using the Chandra HETG spectrometer (Huenemoerder et al. 2013a, 2013b). The RESIK observations have a spectral resolution of 11 eV (11.5 mA), and the Chandra HETG spectra a spectral resolution of 12 eV (12 mA). These are considerably better than the ~100 eV resolution of the MOS and PN CCD detectors on XMM-Newton. Consequently, the individual members of the K XVIII line complex (w, x + y, z lines: notation of Gabriel 1972) at 3.473, 3.493, and 3.511 keV (photon energies based on wavelengths from Kelly 1987) are well resolved in the solar flare spectra. Moreover, analysis of the well-calibrated RESIK instrument allows absolute abundance determinations, and from 2795 individual spectra recorded during 20 flares between 2002 and 2003, Sylwester et al. (2010b) determined the mean K abundance (on a logarithmic scale with A(H) = 12) to be A(K) = 5.86 ± 0.23 (s.d.), a factor of nearly seven times the solar photospheric abundance of Asplund et al. (2009) (A(K) = 5.03 ± 0.09) or a factor of nearly six higher than that of Caffau et al. (2011) ((A(K) = 5.11 ± 0.09). Such deviations of solar coronal abundances from photospheric abundances are well known and have been found to depend on the first ionization potential (FIP) of an element (see Section 3).

In this paper, we extend the work of Sylwester et al. (2010b) by the addition to RESIK data sets of several thousand spectra, with the consequence that our previous K abundance estimate for all RESIK flares is revised upwards. We then examine whether the spectral signatures recorded by Bulbul et al. (2014a) and Boyarsky et al. (2014a) are compatible with the K XVIII line emission based on these solar flare observations, and whether there is a need for invoking sterile neutrino decay.

2. OBSERVATIONS

The RESIK instrument (Sylwester et al. 2005) was a high-resolution crystal spectrometer on the CORONAS-F spacecraft, and was operational over the period 2002–2003 when solar activity was at a high level. The full spectral range of the instrument for an on-axis source, covered by four channels, was 2.05–3.69 keV (wavelength range 3.36–6.05 Å). The spectral range was slightly extended for off-axis sources. Channel 1 (spectral range 3.26–3.69 keV) includes the He-like K (K XVIII) lines mentioned earlier as well as H-like S (S XVI) and Ar (Ar XVIII) Lyman lines and a dielectronic satellite line feature at 3.62 keV due to Ar XVI made up of several lines but with one major contributor. Our earlier analysis (Sylwester et al. 2010b) was based on 2795 spectra recorded in 20 flares. For this work, many additional flare spectra were added to a scientifically analyzable level (so-called Level 2; see http://www.cbk.pan.wroc.pl/experiments/resik/RESIK_Level2/index.html), giving a total of 9295 spectra occurring during 101 flares. Figure 1 (black line) shows the summed spectrum of the entire data set, so includes spectra over all development stages of the flares.
analyzed. The principal lines occurring in this range are identified by the emitting ions in this figure. Over-plotted in this figure (red lines) are synthetic spectra from the CHANTEL database and spectral code (Dere et al. 1997; Landi et al. 2012). The observed spectra were convolved with a Gaussian profile having FWHM equal to 100 eV to match the energy resolution of the MOS and PN detectors on XMM-Newton; these are shown as the blue lines.

More details of the spectral lines of interest are given in Table 1. This table gives all significant lines occurring in the energy range of RESIK channel 1 as well as neighboring regions, including RESIK channels 2–4, for comparison with the lines listed by Bulbul et al. (2014a). A few errors in the Bulbul et al. (2014a) list are corrected and photon energies (from the wavelengths of Kelly 1987) and transitions added with estimates of maximum contribution functions (emissivities). Note that there are four K xviii lines (w, x, y, and z) and not just two (w and z) as stated by Bulbul et al. (2014a) and Jeltema & Profumo (2015). Figure 1 shows that at the 100 eV resolution, the only recognizable line features above the continuum level are one due to the K xviii lines and a second due to the combined S xvi Lyα and Ar xvii Lyα lines. The prominent Ar xvii w3 line at 3.685 keV is on the high-energy edge of RESIK channel 1 and was not generally visible, although for flares with high spatial offset from the Sun’s center this line sometimes fell within the observed channel 1 limits.

Figure 2 shows RESIK channel 1 spectra extracted from the new data set and summed over narrow regions of temperature $T_{\text{GOES}}$, taken to be that estimated from the flux ratio of the two X-ray channels of the Geostationary Operational Environmental Satellites (GOES). Our previous work has indicated that $T_{\text{GOES}}$ is an accurate representation of temperature for the K xviii lines as well as Ar xvii lines seen in channel 2 (Sylwester et al. 2010a). The emission measures EM$_{\text{GOES}}$ (emission measure = $N_e^2 V$ where $N_e$ = electron density and $V$ = emitting volume) for each RESIK spectrum were estimated from the ratio of the observed spectral flux to the theoretical spectral flux from the CHANTEL code at the temperature $T_{\text{GOES}}$. The vertical scale in Figure 2 is flux (photons cm$^{-2}$ s$^{-1}$ keV$^{-1}$) normalized to a volume emission measure of 10$^{48}$ cm$^{-3}$. Through a careful adjustment of pulse-height analyzers during the CORONAS-F mission, crystal fluorescence background emission was practically eliminated for RESIK channels 1 and 2, so the background levels indicated for each spectrum of Figure 2 are solar continuum. With the exception of the Ar xvi satellite feature at 3.62 keV, the lines are progressively stronger with increasing $T_{\text{GOES}}$ and the continuum slope is progressively flatter with increasing $T_{\text{GOES}}$.

The spectral resolution of RESIK channel 1 is such that the K xvi w, x, y, and z lines are apparent as three separate line features. We cannot state with certainty whether RESIK sees the Cl xvi Lyα line (3.507 keV), mentioned as possibly present in XMM-Newton spectra of galaxy clusters and individual galaxies Jeltema & Profumo (2015). The Cl xvi Lyα line, which should be more intense, occurs at the low-energy edge of RESIK channel 2 and is blended with a dielectronic satellite of S xiv; the blended feature has been observed in the spectra of some flares with high spatial offsets but the line flux is uncertain because of its vicinity to the end of the crystal range. However, the Cl xvi Lyα line has recently been recorded in channel 3 during many flares and from which a solar flare chlorine abundance (Sylwester et al. 2011) has been estimated (A(Cl) = 5.75 ± 0.26), compared with A(Cl) = 5.5 from an early analysis of HCl sunspot spectra by Hall & Noyes (1972) (see remarks on the latter determination by Asplund et al. 2009). Other lines are expected in the region of the K xvi lines, in particular K xvi dielectronic satellites, the fluxes of which were calculated by Sylwester et al. (2010b). The most significant include satellites j and k (3.474, 3.477 keV, respectively), which are blended with K xvi line z, and d13 and d15 (3.503 keV) which are blended with K xvi line w. At temperatures <1 keV, the fluxes of j and k are calculated to be comparable to K xvi line z but decreasing for higher temperatures (the satellite-to-line w ratio has an approximately $T^{-1}$ dependence).

The greatly extended RESIK channel 1 data set has allowed us to refine the determination of the solar flare K abundance adopting the same method used in our previous analyses. For each spectrum, continuum fluxes in units of photon cm$^{-2}$ s$^{-1}$ bin$^{-1}$ on either side of the K xvi line group were measured and an average value calculated; in this spectral region, a RESIK energy bin is approximately 1.54 eV (1.56 mA). The energy intervals containing only continuum were 3.462–3.465 keV and 3.529–3.543 keV. The total flux $F_{\text{K xvi}}$ in the K xvi w, x, y, and z lines together with continuum was then determined over the energy interval 3.465–3.520 keV. With $N_1$, $N_2$, and $N_3$ the number of RESIK energy bins in the 3.462–3.465 keV, 3.529–3.543 keV, and 3.465–3.520 keV, the total flux in the K xvi w, x, y, and z lines is therefore

$$F_{\text{K xvi}} = F(3.465–3.520) - N_3 \times C_{\text{av}}$$

where $C_{\text{av}}$ is

$$C_{\text{av}} = \frac{1}{2} \times \left\{ F(3.462–3.465)/N_1 + F(3.529–3.543)/N_2 \right\}.$$
### Table 1  
Lines Contributing to the 2.0–4.1 keV (3.0–6.2 Å) Solar X-ray Spectra

| Ion | Line Notation | Transition | Energy (keV) | $T_{\text{max}}$ (keV) | Seen by RESIK (Y/N) |
|-----|---------------|------------|-------------|--------------------------|---------------------|
| Si XIV | Lyα | 1s $^2S_{1/2} - 2p^2(^2P)_{1/2,3/2}$ | 2.004, 2.006 | 1.4 | … |
| Al XIII | Lyβ | 1s $^2S_{1/2} - 3p^2(^2P)_{1/2,3/2}$ | 2.048 | 1.1 | … |

**RESIK Channel 4**  
(2.05–2.48 keV)

| Si XII | D4 | 1s $^2P_{1/2} - 1s^2(2P) 4p^2(3D_{5/2})$ | 2.228 | 0.8 | Y^e |
| Si XIII | w3 | 1s $^2S_{0} - 1s^3p^1 P_1$ | 2.183 | 1.0 | Y |
| Si XIII | w4 | 1s $^2S_{0} - 1s^4p^1 P_1$ | 2.294 | 1.0 | Y |
| Si XIII | w5 | 1s $^2S_{0} - 1s^5p^1 P_1$ | 2.346 | 1.0 | Y |
| Si XIV | Lyβ | 1s $^2S_{1/2} - 3p^2(^2P)_{1/2,3/2}$ | 2.376, 2.377 | 1.4 | Y |
| S XV | z | 1s $^2S_{0} - 1s^2 2S_1$ | 2.431 | 1.4 | Y |
| S XV | x + y | 1s $^2S_{0} - 1s^2 P_{1/2}$ | 2.447 | 1.4 | Y |
| S XV | w | 1s $^2S_{0} - 1s^2 P_{1/2}$ | 2.461 | 1.4 | Y |
| Si XIV | Lyγ | 1s $^2S_{1/2} - 4p^2(^2P)_{1/2,3/2}$ | 2.506 | 1.4 | Y |

**RESIK Channel 3**  
(2.55–2.85 keV)

| Si XIV | Lyδ | 1s $^2S_{1/2} - 5p^2(^2P)_{1/2,3/2}$ | 2.566 | 1.4 | Y |
| S XVI | Lyα | 1s $^2S_{1/2} - 2p^2(^2P)_{1/2,3/2}$ | 2.620, 2.623 | 2.2 | Y |
| Cl XVI | z | 1s $^2S_{0} - 1s^2 2S_1$ | 2.757 | 1.5 | Y^d |
| Cl XVI | x + y | 1s $^2S_{0} - 1s^2 P_{1/2}$ | 2.775 | 1.5 | Y^d |
| Cl XVI | w | 1s $^2S_{0} - 1s^2 P_{1/2}$ | 2.790 | 1.5 | Y^d |
| S XV | D3 | 1s $^2P_{1/2} - 1s^2(2P) 3p^2(3D_{5/2})$ | 2.817 | 1.1 | Y |
| S XV | w3 | 1s $^2S_{0} - 1s^3p^1 P_1$ | 2.884 | 1.4 | Y |

**RESIK Channel 2**  
(2.90–3.24 keV)

| S XV | D4 | 1s $^2P_{1/2} - 1s^2(2P) 4p^2(3D_{5/2})$ | 2.957 | 1.1 | Y^d |
| Cl XVII | Lyα | 1s $^2S_{1/2} - 2p^2(^2P)_{1/2,3/2}$ | 2.958, 2.963 | 2.4 | Y^d |
| S XV | w4 | 1s $^2S_{0} - 1s^2 P_1$ | 3.033 | 1.4 | Y |
| S XV | w5 | 1s $^2S_{0} - 1s^5p^1 P_1$ | 3.101 | 1.4 | Y |
| Ar XVIII | z | 1s $^2S_{0} - 1s^2 2S_1$ | 3.104 | 1.9 | Y^e |
| S XVI | Lyβ | 1s $^2S_{1/2} - 3p^2(^2P)_{1/2,3/2}$ | 3.107 | 2.2 | N^e |
| Ar XVII | x + y | 1s $^2S_{0} - 1s^2 P_{1/2}$ | 3.124 | 1.9 | Y |
| Ar XVII | w | 1s $^2S_{0} - 1s^2 P_{1/2}$ | 3.140 | 1.9 | Y |
| S XV | w6 | 1s $^2S_{0} - 1s^5p^1 P_1$ | 3.140 | 1.4 | Y |

**RESIK Channel 1**  
(3.26–3.69 keV)

| Cl XVI | w3 | 1s $^2S_{0} - 1s^3p^1 P_1$ | 3.272 | 1.5 | N |
| S XVI | Lyγ | 1s $^2S_{1/2} - 4p^2(^2P)_{1/2,3/2}$ | 3.277 | 2.2 | Y |
| Ar XVIII | Lyα | 1s $^2S_{1/2} - 2p^2(^2P)_{1/2,3/2}$ | 3.323 | 3.1 | Y |
| S XVI | Lyβ | 1s $^2S_{1/2} - 3p^2(^2P)_{1/2,3/2}$ | 3.355 | 2.2 | Y |
| S XVI | Lyδ | 1s $^2S_{1/2} - 6p^2(^2P)_{1/2,3/2}$ | 3.398 | 2.2 | Y |
| S XVI | Lyγ-Lyχ | 1s – 7p to 1s – 10p | 3.423–3.459 | 2.2 | Y^e |
| K XVIII | z | 1s $^2S_{0} - 1s^2 2S_1$ | 3.472 | 2.2 | Y |
| K XVIII | x + y | 1s $^2S_{0} - 1s^2 P_{1/2}$ | 3.493 | 2.2 | Y |
| S XVI | Series limit | 1s – ∞ | 3.494 | – | N? |
| Cl XVIII | Lyδ | 1s $^2S_{1/2} - 3p^2(^2P)_{1/2,3/2}$ | 3.507 | 2.4 | N |
| K XVIII | w | 1s $^2S_{0} - 1s^2 P_1$ | 3.510 | 2.2 | Y |
| Ar XVI | D3 | 1s $^2P_{1/2} - 1s^2(2P) 3p^2(3D_{5/2})$ | 3.615 | 1.5 | Y |
| Ar XVII | w3 | 1s $^2S_{0} - 1s^3p^1 1P_1$ | 3.685 | 1.9 | Y |
| K XIX | Lyα | 1s $^2S_{1/2} - 2p^2(^2P)_{1/2,3/2}$ | 3.699, 3.704 | 3.8 | … |
| Ar XVI | D4 | 1s $^2P_{1/2} - 1s^2(2P) 4p^2(3D_{5/2})$ | 3.794 | 1.5 | … |
| Ca XIX | z | 1s $^2S_{0} - 1s^2 2S_1$ | 3.861 | 2.4 | … |
| Ar XVII | w4 | 1s $^2S_{0} - 1s^4p^1 P_1$ | 3.875 | 1.9 | … |
| Ca XIX | y | 1s $^2S_{0} - 1s^2 P_1$ | 3.884 | 2.4 | … |
| Ca XIX | x | 1s $^2S_{0} - 1s^2 P_1$ | 3.888 | 2.4 | … |
| Ca XIX | w | 1s $^2S_{0} - 1s^2 P_1$ | 3.903 | 2.4 | … |
| Ar XVII | Lyβ | 1s $^2S_{1/2} - 3p^2(^2P)_{1/2,3/2}$ | 3.936 | 3.1 | … |
| Ar XVII | w5 | 1s $^2S_{0} - 1s^5p^1 P_1$ | 3.964 | 1.9 | … |
Note that the very slight contributions made by the SXVI high-\(n\) lines and ClXVII line in the vicinity of the KXVIII lines were neglected. Using the temperature and emission measure obtained from GOES channel ratios as earlier described, the irradiances of the KXVIII lines were found from

\[ I_{EM} \times 10^{48} \]

These irradiances are plotted for each spectrum analyzed against \(T_{GOES}\) in Figure 3 (left panel). As expected, the distribution of points has the same temperature dependence as the theoretical contribution function, calculated from CHIANTI, for the KXVIII lines using the photospheric K abundance of \(A(K) = 5.03\) (Asplund et al. 2009) shown as the red curve. The scatter of points reflects the weakness of the KXVIII lines in RESIK spectra, but it is clear from the displacement of the points above the red curve that the flare abundance is considerably larger than the photospheric. An estimate of the abundance RESIK spectra is possible through the deviation of each plotted point in Figure 3 (left panel) from the theoretical contribution function; the distribution of these estimates against the estimated value of \(A(K)\) is shown as a histogram plot in Figure 3 (right panel). The best-fit Gaussian to the distribution is also shown, the peak and width of which give our estimate of the solar flare K abundance, \(A(K) = 6.06 \pm 0.34\) (s.d.). This should be compared with the result from our previous smaller sample of solar flares (Figure 3 of Sylwester et al. 2010b), in which we derived
A(K) = 5.86 ± 0.23. The present abundance estimate is a factor of approximately 11 higher than the photospheric abundance of Asplund et al. (2009).

Our estimate of the solar flare abundance relies heavily on the atomic data for helium-like potassium in the CHIANTI database, in particular the values of the effective collision strengths which, in the absence of specific calculations available for the release of CHIANTI v. 7, are based on interpolations of helium-like ions of other elements. Since errors in these values folded directly into the abundance determinations, it is advisable to check the accuracy of the atomic data wherever possible. Since our earlier work (Sylwester et al. 2010b), new calculations have appeared (Aggarwal & Keenan 2012) based on the DARC (Dirac Atomic R-matrix Code) for K XVIII and other He-like ions. We compared the effective collision strengths for the principal atomic transitions involved in the K XVIII, w, x, y, and z lines finding, for the temperature range of interest ($T_{\text{GOES}} > 0.4$ keV or >4.6 MK), only a few percent differences. This vindication of the atomic data used in our analysis based on CHIANTI thus adds confidence to our abundance estimates.

### 3. DISCUSSION AND CONCLUSIONS

Using a much extended data-base of solar flare spectra (spectral resolution 11 eV) from the RESIK instrument on CORONAS-F spacecraft over our earlier analysis (Sylwester et al. 2010b), our estimates of the K XVII line irradiance lead to a solar flare abundance of K of $A(K) = 6.06 \pm 0.34$ or a factor of 11 more than the photospheric abundance of Asplund et al. (2009) ($A(K) = 5.03 \pm 0.09$) or a factor 9 more than that of Caffau et al. (2011) ($A(K) = 5.11 \pm 0.09$). Our present abundance estimate is slightly more than was found in an earlier, less complete analysis of RESIK spectra ($A(K) = 5.86 \pm 0.23$; Sylwester et al. 2010b). It may also be compared with the value $A(K) = 5.7$ adopted from analysis of a (K X) far-ultraviolet line observed with the Coronal Diagnostic Spectrometer on Solar and Heliospheric Observatory (Landi et al. 2002). Although the K XVII lines are not very strong in RESIK spectra, the plot in Figure 3 (left panel) clearly shows the enhanced abundance of K. In addition, for the RS CVn binary star system σ Gem observed by Chandra, the K abundance was found to be a factor 4 more than solar photospheric (Huenemoerder et al. 2013a). Such abundance anomalies are well documented for the solar corona, particularly solar flare plasmas, and are commonly attributed to the “FIP effect” because of an apparent dependence on the value of the FIP of element abundances in the solar corona and solar wind particles (Meyer 1985; Feldman 1992; Feldman & Laming 2000): low-FIP elements (i.e., FIP ≤ 10 eV) are generally observed to have coronal abundances enhanced with respect to photospheric but high-FIP elements are not. The exact nature of the FIP effect in flare plasmas is still being actively discussed by several authors. For Si (FIP = 8.2 eV), a recent analysis of RESIK observations (Sylwester et al. 2015) indicate no enhancement over photospheric, while for Fe (FIP = 7.9 eV), Dennis et al. (2015) from X-ray spectra found only a modest enhancement over photospheric and Warren (2014) using extreme ultraviolet spectra found none at all. This possibly indicates that the boundary between high-FIP and low-FIP elements is less than 10 eV. Comparison with element abundances from solar energetic particle observations (e.g., Zurbuchen et al. 2002; Reames 2014) is more problematic. First, impulsive particle events show large time variations and most analyses eliminate such events from averaged abundance values. Also, recovery of abundances at the coronal sources of particle events must take account of differential transport effects which are considerable. With these and other provisos in mind, Reames (2014) finds that averaged abundance estimates for 54 gradual solar particle events show a K abundance enhancement over the Caffau et al. (2011) photospheric abundance of only 2 (range 1.7–3). A difference in the nature of the FIP effect for solar energetic particles in
interplanetary space and those from X-ray and ultraviolet observations, which refer to closed magnetic structures in the solar corona, is thus indicated. All these findings are relevant to theoretical mechanisms for the FIP effect which have been discussed by Hénoux (1998) and Laming (2012).

The ∼3.5–3.57 keV spectral region has been observed with XMM-Newton by Bulbul et al. (2014a) in 73 galaxy clusters and by Boyarsky et al. (2014b) in the Perseus galaxy cluster and the Andromeda galaxy M31. The line feature noted by Bulbul et al. (2014a) at 3.47–3.51 keV has >3σ significance in stacked XMM-Newton spectra, though this is disputed by Jeltema & Profumo (2015). The interval over which the emission is enhanced, 3.55–3.57 keV, is very close to that of the energy range of the K xvi w − z line emission. Bulbul et al. (2014a) analyzed the XMM-Newton data using the AtomDB atomic physics package with solar photospheric abundances from Anders & Grevesse (1989). More recent and comprehensive lists of photospheric abundances are given by Asplund et al. (2009) and Caffau et al. (2011), with minor revisions to the abundances of elements relevant to the work of Bulbul et al. (2014a) and Jeltema & Profumo (2015). Using A(K) = 5.13 (given as 5.03 ± 0.09 by Asplund et al. 2009 and 5.11 ± 0.09 by Caffau et al. 2011; Bulbul et al. 2014a) dismiss the identification of the 3.47–3.51 keV emission feature as K x vii lines on the grounds that fits with the AtomDB package assuming a collisional ionization and excitation model require a K abundance of a factor of ∼20 over the solar photospheric value (although this depends on the temperature model that they use), and instead attribute the feature to the decay of sterile neutrinos, a dark matter candidate, with mass 7.1 keV. The factor ∼20 that Bulbul et al. (2014a) state the photospheric abundance of K needs to be enhanced is derived from a temperature model using a fit to the continuum from APEC in the XSPEC spectroscopy modeling procedure, with temperatures between 6 and 10 keV. However, these high temperatures disagree with the observed ratio of Ca xix to Ca x x lines (Jeltema & Profumo 2014).

Clearly, the case for identifying the 3.55–3.57 keV feature to sterile neutrino decay is much weakened if the X-ray emission sources observed by XMM-Newton have an origin like solar flare plasmas for which K is enhanced by some mechanism. Much of the emission from galaxy clusters arises from intracluster thermal plasmas in collisional ionization and excitation equilibrium with temperatures in the range 1–10 eV (Sarazin 2003). If a magnetic mechanism like a ponderomotive force as proposed by Laming (2012) for solar coronal plasmas is involved in the origin of this hot gas, then enhancements of K could result. For the case of individual galaxies like M31, the X-ray emission above 2 keV, with luminosities of 10^{39}–10^{40} erg s^{-1}, is mostly from spatially unresolved high-luminosity low-mass X-ray binary systems (Takahashi et al. 2004) with combined estimated X-ray luminosity of up to ∼5 × 10^{39} erg s^{-1}; no single black hole or similar accretion source is dominant or even significant. At softer energies, there is a diffuse emission attributed to thermal plasma with temperatures <1 keV. If the origin of the X-ray emission from the X-ray binaries is a ponderomotive force associated with Alfvén waves, then abundance enhancements in K like those in solar flare plasmas could arise if the gas being accreted by the evolved component of the binary system has its origin in the outer atmosphere of the donor (unevolved) star. The K abundance enhancement estimated here from RESIK solar flare spectra only needs a factor of ∼1.8 to explain the factor 20 mentioned by Bulbul et al. (2014a), and this could easily be explained by the 100 eV spectral resolution and the very low statistical significance of their signal, even in the summed spectra of the galaxy clusters that they observed with XMM-Newton. This could also explain the slight difference in the energy of the observed feature (3.55–3.57 keV) and the range of the K x viii lines (3.47–3.51 keV).

In addition to the K x viii lines, small contributions may be made by the Cl x x vii Lyβ line at 3.507 keV, very near the K x viii w line, as noted by Jeltema & Profumo (2015). To estimate this contribution, we use RESIK observations of the Cl xvi w, x + y, and z lines (2.76–2.79 keV) from which a chlorine abundance A(Cl) = 5.75 ± 0.26 was derived (Sylwester et al. 2011). This is consistent with the estimate of Hall & Noyes (1972) from a sunspot HCl spectrum, A(Cl) = 5.5 ± 0.3, as is expected from the solar coronal FIP effect with the high value of chlorine’s FIP (12.97 eV). Using the RESIK solar flare abundance estimates of Cl and K (from this work), we estimate that only about 2% of the 3.55–3.57 keV emission is due to Cl at a temperature of 2 keV, but increasing to 13% for 5 keV (one of the temperatures given by Bulbul et al. 2014a). Thus, we confirm the calculation made by Jeltema & Profumo (2015) that Cl does not seem to be a dominant contributor to the K x viii line emission.

High-n hydrogen-like S (K x vii) lines occur in the 3.55–3.57 keV region, as indicated by Table 1, in particular the series limit of these lines occurs between the K x vii w and x + y lines in RESIK solar flare spectra. Figure 1 and the highest-temperature panel of Figure 2 certainly show the S x vii Lyδ and Lyε lines (3.355 and 3.398 keV) with possible evidence of higher-n members, but it is evident that their contribution to the K x viii lines is insignificant.

In summary, solar flare spectra from the RESIK instrument on CORONAS-F indicate a mean coronal potassium abundance which is a factor of between 9 and 11 higher than the solar photospheric abundance. For solar coronal plasmas, some mechanism operates to enhance the coronal abundances of elements with low FIP, possible ones being discussed by Hénoux (1998) and Laming (2012). However, the boundary between high-FIP and low-FIP elements, previously cited to be 10 eV, is not completely established, recent X-ray and extreme ultraviolet spectroscopic flare observations indicating that Si and Fe (FIP = 8.2 eV, 7.9 eV, respectively) are either not enhanced at all or are only slightly enhanced over photospheric. If this or some equivalent mechanism applies to the stellar component of X-ray emission in individual galaxies or the high-temperature gas in galaxy clusters, the observed line feature at 3.55–3.57 keV is readily explained, particularly in view of the low statistical quality of the X-ray spectra from XMM-Newton obtained by Bulbul et al. (2014a), and thus a sterile neutrino interpretation of the observed line feature at ∼3.5 keV is unnecessary.

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