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* Manuscript

Temperature-sensitive Line Ratio Diagnostics based on Si Satellite-to-Resonance Line Ratios for $1s^2 - 1snp$ Transitions

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Abstract

Dielectronic satellite lines due to $1s^2\,n'l' - 1snp\,n'l'$ ($n = 3$, 4) transitions in Li-like Si (Si XII) occur at 5.818 Å and 5.565 Å, on the long wavelength side of the He-like Si (Si XIII) $1s^2 - 1s3p$ and $1s^2 - 1s4p$ lines at 5.681 Å and 5.384 Å respectively. They have been extensively observed with the RESIK crystal spectrometer on the Russian spacecraft *CORONAS-F*. As with corresponding satellites $1s^2\,nl - 1s2p\,nl$ on the long-wavelength side of the Si XIII $1s^2 - 1s2p$ resonance line, there is an inverse temperature dependence of the intensity ratio of the satellites to the He-like ion lines ($I_{\rm sat}/I_{\rm He}$). New atomic data are used to calculate the Si XII satellite line intensities and thus the $I_{\rm sat}/I_{\rm He}$ ratio. RESIK observations of the ratio in solar flares, together with temperatures from the ratio of the two *GOES* X-ray channels, are compared with theoretical variation of the ratio with temperature. The good agreement indicates this to be a valuable temperature diagnostic for solar flares and laboratory plasmas such as tokamaks. There are implications for similar satellites in Fe line spectra which are observed with broad-band resolution by the *RHESSI* solar flare mission.

Key words: Sun, X-ray, spectra

1 Introduction

The REntgenowsky Spektrometr s Izognutymi Kristalami (RESIK) instrument on the Russian *CORONAS-F* mission, launched on 2001 July 31, has obtained spectra in the wavelength range 3.4 Å–6.1 Å during the course of many solar flares. The 4.96 Å–6.09 Å range, covered by channel 4 of RESIK, includes He-like Si (Si XIII) lines due to the transitions $1s^2 - 1snp$, $n = 3$, 4, 5. Satellite lines due to transitions $1s^2\,n'l' - 1snp\,n'l'$ in Si XII ('spectator' electron specified by $n'l'$, those with $n'l' = 2s$ or $2p$ being the most intense) form prominent features on the long-wavelength side of the He-like lines. Preliminary results have been presented by Sylwester et al. (2002), while instrumental details are given by Sylwester et al. (2004b). Intensity and wavelength calibration has been achieved through a combination of pre-flight laboratory and published data; count rate spectra can be converted to flux unit spectra via routines using these data written by the RESIK instrument team. The Si XII satellites are of considerable interest since the ratios of the satellites to the nearby parent (He-like) line are temperature-sensitive, so offering a means of diagnozing the flare plasma in the absence of similar ratios involving Si XII $1s^2\,n'l' - 1s2p\,n'l'$ satellites which are not included in the RESIK wavelength range.

Atomic parameters for the satellites have been calculated by one of us (J.D.) and are used here to derive theoretical intensity ratios of the satellites to the He-like ion lines. We use observations of these ratios during the course of long-duration X-ray flares observed by RESIK. We compare the observed and theoretical ratios using temperatures from *GOES* X-ray data, showing that the agreement is very close.

2 Observations and Analysis

We selected four long-duration flares observed by RESIK in 2002, used in a previous analysis (Phillips et al. 2003) of line intensities to obtain abundances of K, Ar, and S. The flares occurred on April 14/15, July 11, July 22/23, and July 26/27. Emission detected by channel 4 of RESIK covering the Si lines is diffracted by quartz crystal (diffracting plane $10\bar{1}0$), $2d$ spacing 8.51 Å and rocking curve (FWHM) 0.62 mÅ. The spectral resolution has been empirically determined to be 15.7 mÅ from line widths during periods of relative quiescent solar conditions. Fig. 1 shows nine spectra (data gathering intervals varying between 5 and 20 minutes) during the course of the several-hour decay of the July 26/27 flare, with times (UT) indicated. The Si XIII lines at 5.681 Å and 5.384 Å are due to $1s^2 - 1s3p$ (Heβ) and $1s^2 - 1s4p$ (Heγ) transitions respectively, and are prominent at earlier times (as are He-like S lines at shorter wavelengths). At later times, the Si XII satellite line features at 5.818 Å and 5.565 Å (called here A and B respectively) are relatively more intense; the 5.818 Å feature is comparable in intensity to the 5.681 Å line some nineteen hours after the flare maximum, near 21:22 UT on July 26. There is a marked decrease in temperature T, as indicated by the ratio of *GOES* X-ray channels, for later times in this flare, so the intensity ratio of the satellites to the He-like ion lines is clearly inversely related to T.

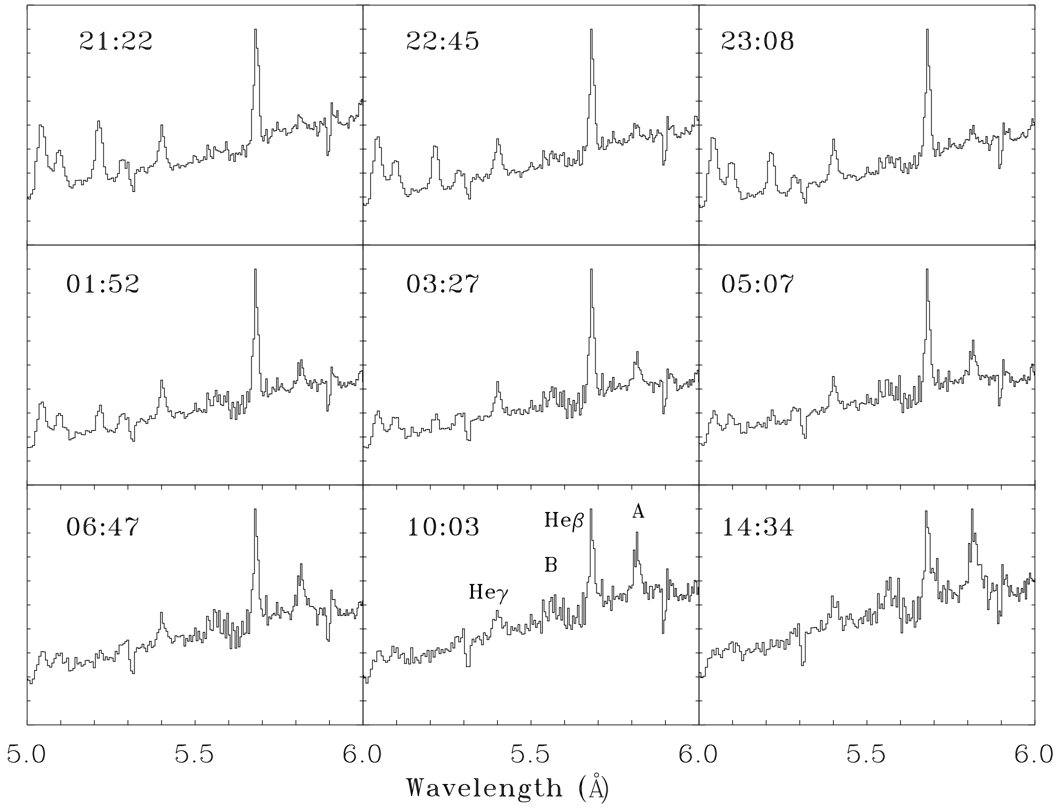

Fig. 1. RESIK channel 4 spectra during the flare of 2002 July 26/27 (times, UT, indicated), illustrating the changing intensities of the Si XII satellite features (A, 5.818 Å and B, 5.565 Å) relative to the Si XIII Heβ (5.681 Å) and Heγ (5.384 Å) lines. These lines are indicated in the 10:03 UT plot. The fluorescence background has not been subtracted from these spectra.

RESIK spectra for times during all four flares were analyzed by finding best-fit Gaussian profiles to the line emission whenever this was feasible. A pre-flare spectrum was subtracted from each flare spectrum analyzed. For most spectra, the measured Si XIII lines intensities have uncertainties (taking account of the pre-flare spectrum subtraction) of $\sim 15\%$, while the Si XII satellites have larger uncertainties for times near the peak of each flare when they are relatively much weaker. The ratios A/Heβ and B/Heγ were obtained for each time interval. For these same intervals, the *GOES* temperature T was obtained, again subtracting a pre-flare level taken at the same time as the RESIK pre-flare spectrum. The A/Heβ ratios are plotted in Fig. 2 for the July 23 and July 26/27 flares, with error bars indicating estimated uncertainties.

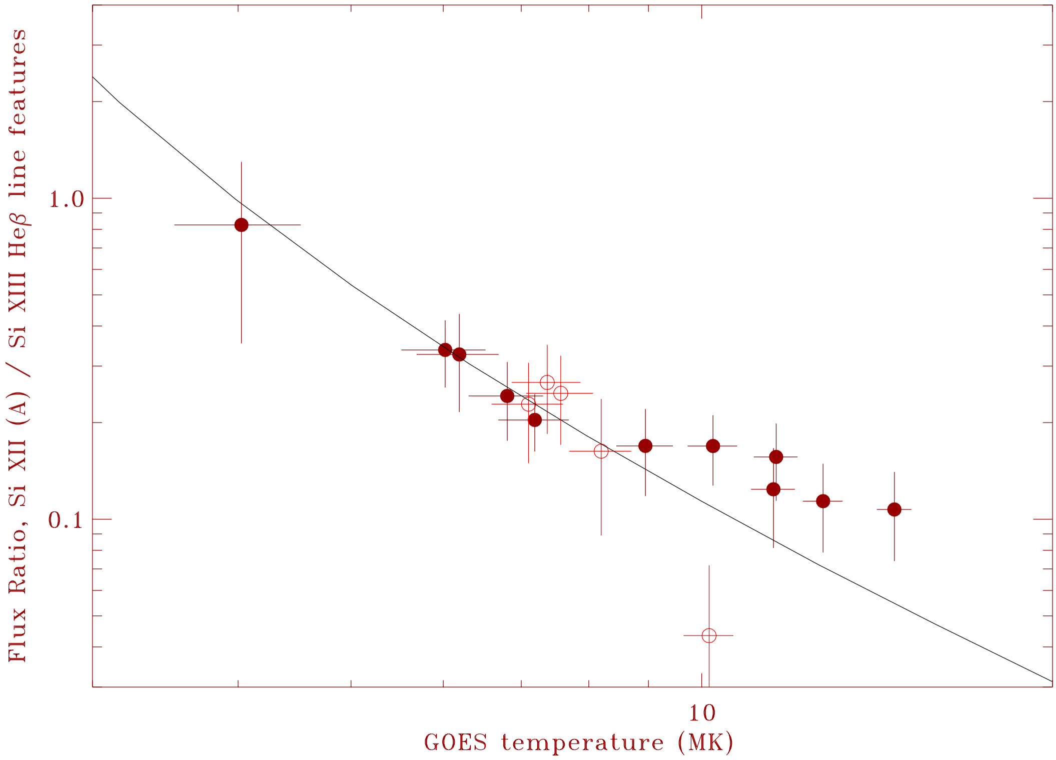

Fig. 2. Observed (points with error bars) values of Si XII A/Si XIII Heβ plotted against T derived from the ratio of the two *GOES* channels over the same time intervals. Open circles: July 23 flare; filled circles: July 26/27 flare. The curve is the theoretical variation calculated using CHIANTI values for the Si XIII Heβ line flux and data described in the text for the Si XII satellites forming the line feature A.

3 Theoretical Line Intensities

The Si XIII Heβ and Heγ lines are formed mainly by electron collisional excitation. With the spectral resolution of RESIK, there are two transitions involved, due to $1s^2\,{}^1S_0 - 1snp\,{}^1P_1$ and $1s^2\,{}^1S_0 - 1snp\,{}^3P_1$, the former much more intense than the latter. The Si XII satellites making up the A and B features are formed by dielectronic recombination. Gabriel (1972) gives details of the excitation rates, which are a function of T and an intensity factor $F_{\rm sat}$ which depends on radiative and autoionization rate coefficients from the doubly excited upper state. The CHIANTI atomic database and code gives line fluxes for the Si XIII lines and for the Si XII satellite feature A but not B. We therefore used calculations of wavelengths, values of $F_{\rm sat}$ and other atomic data for the satellites making up features A and B done by one of us (J.D.). Generally, satellites with transitions $1s^2 2p\,^2P_{3/2} - 1s2p\,np\,^2D_{5/2}$ and $1s^2 2p\,^2P_{1/2} - 1s2p\,np\,^2D_{3/2}$ dominate A ($n = 3$) and B ($n = 4$); they correspond to the intense satellites j and k for the more familiar $n = 2$ satellites (Gabriel (1972)). The theoretical ratios depend approximately on $F_{\rm sat}/T$. That for all satellites making up feature A are plotted against T in Fig. 2, along with the observed points.

4 Results and Conclusions

There is a very close agreement between the observed points and theoretical curve plotted in Fig. 2 for the Si XII A/Si XIII Heβ line ratio. Most points agree to within the estimated uncertainties. There are fewer observed values of the Si XII B/Si XIII Heγ and the uncertainties are larger, but there is a general agreement with the theoretical curve. In this preliminary work, we are aware of the possible uncertainty in values of temperature derived from the two *GOES* channels using a standard routine in the *SolarSoft* IDL package. This package is based on ratios empirically derived by Thomas et al. (1985), though newer line and continuum data from CHIANTI will probably modify the dependence somewhat. In later work, we will use the ratio of the total flux in two RESIK channels as temperature-indicators which may be more satisfactory. Meanwhile, we may conclude that RESIK observations during long-duration flares of the Si XIII $1s^2 - 1s3p$ and $1s^2 - 1s4p$ lines and nearby Si XII satellites indicate their ratios to be a useful diagnostic of temperature.

RESIK observes corresponding satellite line features near He-like Ar (Ar XVIII) lines (extreme end of channel 1 wavelength range) and He-like S (S XV) lines (channels 2 and 3) during flares. Sylwester et al. (2004a) gives details. Depending on the flare temperature, these satellite features have intensities often exceeding the He-like ion lines themselves. With such lines, other temperature diagnostic information is therefore available. Recognizing the multi-thermal nature of flare plasmas, the ratios of satellites to He-like ion lines may give much more accurate differential emission measures than has hitherto been possible.

Satellites to the $1s^2 - 1s3p$ and $1s^2 - 1s4p$ lines in He-like Fe (Fe XXV) have not, to the authors' knowledge, been observed in solar flare spectra with crystal spectrometer resolution, but they must have intensities that are stronger than Si, S, or Ar because of the strong Z-dependence of the satellite intensity factor $F_{\rm sat}$. The entire complex of Fe XXV lines and satellites form a strong feature in the broad-band resolution of spectra obtained with the *RHESSI* solar flare mission, photon energies around 8 keV (wavelengths ~ 1.5 Å). The ratio of the 8 keV feature to the stronger 6.7 keV line feature, also observed in *RHESSI* spectra, is being used to diagnoze the hottest parts of the flare plasma. Dennis et al. (2004) and Phillips (2004)) discuss this in more detail.

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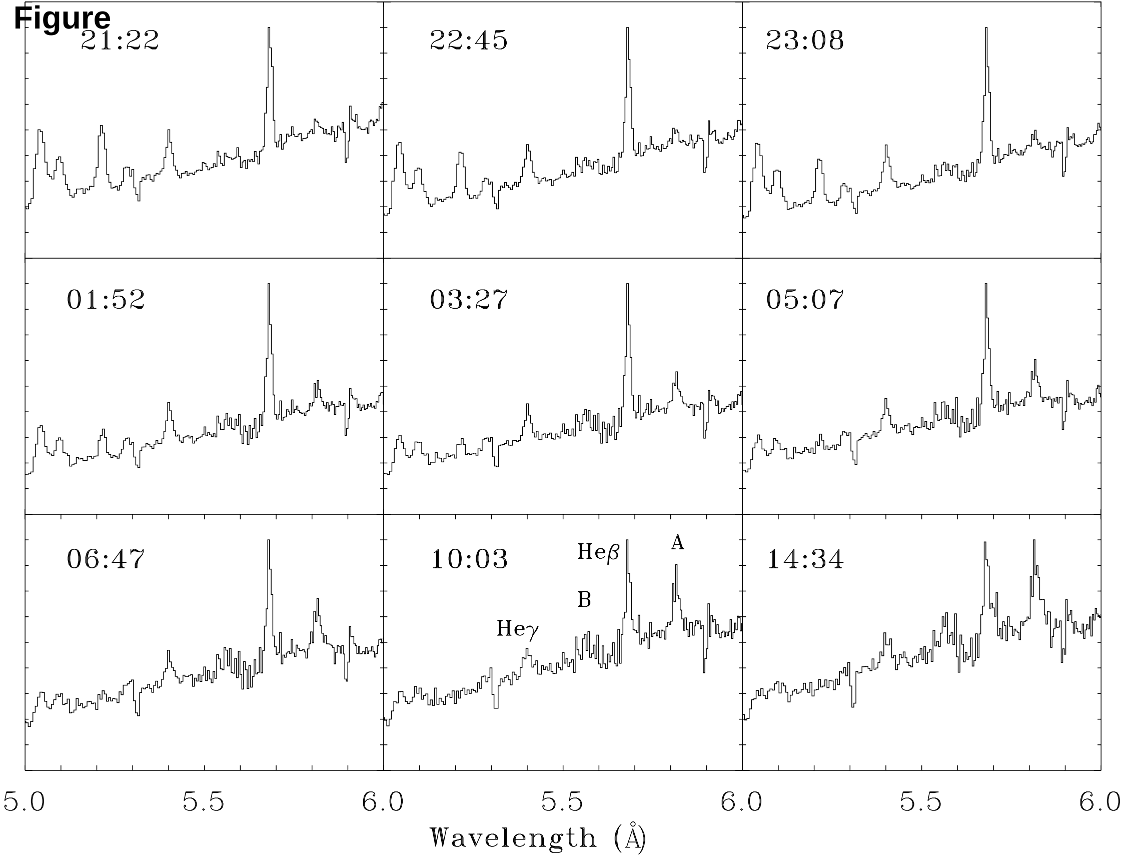
Figure



21:22
22:45
23:08
01:52
03:27
05:07
06:47
10:03
14:34
Heβ
A
B
Heγ
5.0
5.5
6.0
5.5
6.0
5.5
6.0
Wavelength (Å)