Dielectronic Satellites Near the $1s^2 - 1snp$ ($n > 2$) Lines of He-like Ions in Solar X-ray Spectra

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Abstract. We discuss the importance of dielectronic satellites with transitions $1s^2 2l - 1s2l3p$ on the long-wavelength side of He-like ion lines $1s^2 - 1snp$ ($n > 2$). Their intensity ratios with the He-like ion lines have an inverse temperature dependence, making them useful as diagnostics. This is examined in the case of Si and Fe satellites.

Keywords: X-ray spectra – X-ray diagnostics – Satellite lines
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INTRODUCTION

The importance of dielectronic satellites as temperature diagnostics in solar and tokamak soft X-ray spectra is well known, but the satellites in question most generally used are those near the $1s^2 - 1s2p$ lines of He-like ions. These suffer from spectral confusion with other He-like ion lines to the long-wavelength side of the resonance line, notably the forbidden line ($1s^2\,{}^1S_0 - 1s2s\,{}^3S_1$). Relatively little attention has been paid to satellites on the long-wavelength side of $1s^2 - 1snp$ lines of He-like ions in solar spectra, yet their temperature dependence (approximately T^{-1}) is identical to the $1s^2 - 1s2p$ satellites and (owing to the absence of an equivalent forbidden line) there is no spectral confusion. This paper identifies recent solar flare observations of these satellites and their importance for temperature information. RESIK, a high-resolution spectrometer flying on the Russian *CORONAS-F* spacecraft, has made observations of Si XII and S XIV satellites near the (He-like) Si XIII and S XV $1s^2 - 1snp$, n =3, 4, and 5. We find that line ratios of Si and temperatures from *GOES* spacecraft data confirm the T^{-1} dependence. In addition, we discuss spectra from *RHESSI*, which observes solar flare thermal spectra with broad-band resolution (≃1 keV FWHM) at wavelengths less than 4 Å (photon energies > 3 keV); they include line features at 6.7 keV due to Fe XXV $1s^2 - 1s2p$ lines and satellites and at ~ 8 keV which for $T \sim 20$ MK is made up of Fe XXV $1s^2 - 1snp$ ($n > 2$) lines and Fe XXIV satellites of the type discussed here.

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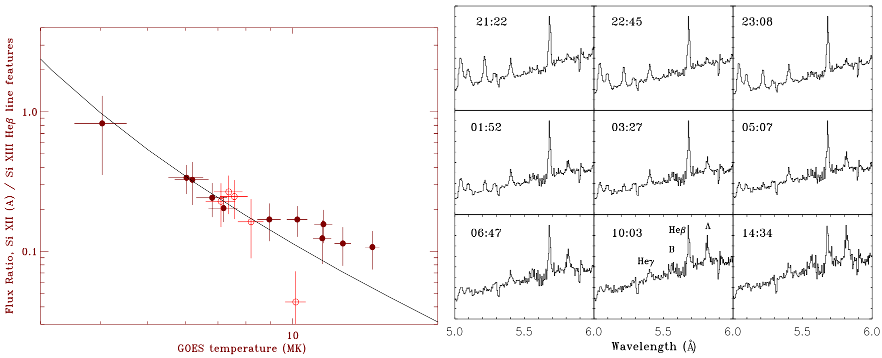

FIGURE 1. **Left**: Measurements of the ratio of the Si XII satellite feature A to the Si XIII Heβ (5.681Å) line vs. *GOES* temperature during long-duration flares on 2002 July 23 (open circles) and 2002 July 26/27 (filled circles) compared with the predicted variation of ratio with temperature from CHIANTI (Dere et al. 1997) and Dubau data. **Right**: RESIK spectra of the 5 to 6 Å region during the solar flare on 2002 July 26/27, showing the Si XIII $1s^2 - 1s3p$ (5.681 Å Heβ) and $1s^2 - 1s4p$ (5.384 Å Heγ) and Si XII satellites at 5.818 Å (A) and 5.565 Å (B). As the flare cools, the satellites become relatively more intense.

SI SATELLITES

The RESIK instrument on *CORONAS-F* which operated as a crystal spectrometer from 2001 till May 2003 made observations of Si XIII lines at 5.681 Å (Heβ, $1s^2\,{}^1S_0 - 1s3p\,{}^1P_1$), 5.384 Å (He$\gamma$, $1s^2\,{}^1S_0 - 1s4p\,{}^1P_1$), and 5.253 Å (He$\delta$, $1s^2\,{}^1S_0 - 1s5p\,{}^1P_1$). To the long-wavelength side of each of these lines is a line feature made of several dielectronic lines, with transitions like $1s^22l - 1s2l3p$. The most intense are those with transitions $1s^22p\,{}^2P_{3/2} - 1s2p3p\,{}^2D_{5/2}$ and $1s^22p\,{}^2P_{1/2} - 1s2p3p\,{}^2D_{3/2}$, equivalent to satellites j and k near the Heα line [2]. The principal mode of excitation of these satellites is dielectronic recombination of the He-like Si ion followed by stabilizing transitions, though inner-shell excitation is important for some satellites. Intensity factors have been calculated by one of us (J.D.), allowing the theoretical intensity ratio of satellite/He-like ion line to be found as a function of T (see Figure 1, left). The T^{-1} temperature dependence is evident.

Observations were made of these lines with RESIK during long-duration flares on 2002 July 26/27 and 2002 July 23 (see [3] for further details). Figure 1, right shows how the intensities of the Si XII satellite features A and B (wavelengths 5.681 Å and 5.565 Å) near the Si XIII Heβ and Heγ lines vary over a 17-hour period during the July 26/27 flare, with the flare slowly decaying and the temperature declining. These observations have been analyzed to give line intensities at various times during each flare. Approximate values of temperature were derived for these times using the ratio of the two X-ray channels of the *GOES* satellites, from standard software available on *SolarSoft*. The measured intensity ratios are plotted against the *GOES* temperatures in Figure 1 (left). The close correspondence illustrates the accuracy of the atomic calculations and the temperature dependence.

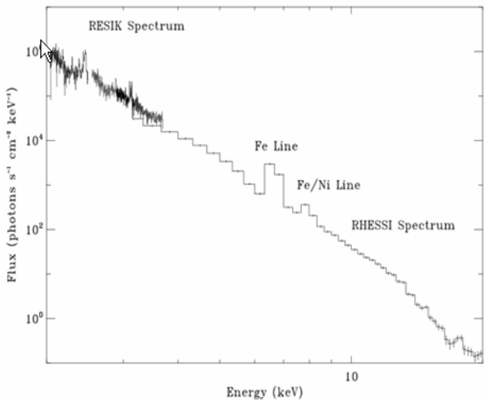

FIGURE 2. *RHESSI* spectrum taken during the flare of 2003 April 26 (03:00 UT) (histogram) and RESIK spectrum plotted against photon energy (range 2-20 keV), showing the Fe line feature at ~ 6.7 keV and Fe/Ni line feature at ~ 8 keV. For the temperature of this spectrum, 18.6 MK, the dominant lines in the Fe/Ni features are Fe XXIV satellites of the type described in the text.

FE SATELLITES

The *RHESSI* mission, looking at solar flares in the 3 keV to 17 GeV energy band, observes line emission at 6.7 keV (1.85Å Å, so-called Fe line feature: see [4]) and 8.1 keV (1.55 Å, Fe/Ni line feature) with broad-band resolution. The Fe line feature is due to Fe XXV lines and dielectronic satellites; the Fe/Ni line feature, at $T < 40$ MK, is due to Fe XXV $1s^2 1snp$ ($n = 3$, 4 etc.) lines and, at $T < 25$ MK, to Fe XXIV satellites $1s^2 2p\,^2P_{1/2} - 1s2p3p\,^2D_{3/2}$ and $1s^2 2p\,^2P_{1/2} - 1s2p4p\,^2D_{3/2}$. The recent addition of these satellites to the CHIANTI code (Dere et al. 1997) has greatly improved the agreement between the observed and theoretical intensity ratio R of the 6.7 keV to the 8.1 keV line feature. The combined *RHESSI* and RESIK spectrum, during the flare of 2003 April 26 at 03:00 UT, shows the (free-free and free-bound) continuum and line emission, with the Fe and Fe/Ni line features marked. The observed and calculated values of the ratio R are both about 10.

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