THE PHOTOSPHERIC-TO-CORONAL IRON ABUNDANCE FROM X-RAY LINES OBSERVED BY YOHKOH AND OTHER SATELLITES

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Abstract

We have analyzed the intensities of photospherically formed Kα lines (1.936, 1.940 Å) and the Fe XXV resonance line (1.850 Å) observed by X-ray spectrometers on the *P78-1* and *S.M.M.* spacecraft to deduce that the photospheric abundance of iron is not significantly different from the coronal abundance, despite recent suggestions that the coronal abundance is up to a factor of about three higher. This result confirms an earlier analysis of *Yohkoh* data using the Kβ line and Fe XXV resonance line features.

1. Introduction

In a discussion of *S.M.M.* data, Parmar *et al.* found that the Kα and Kβ lines of iron present in solar flare X-ray spectra are emitted primarily through the fluorescence of the photosphere beneath the hot ($T_e \approx 20 \times 10^6$K) flaring plasma situated in the low corona. The Kα lines form a doublet, at 1.936 and 1.940 Å, and the strongest Kβ line emission appears as a line feature at 1.757 Å. Photon emission occurs when $1s$ electrons in neutral iron atoms are removed by X-ray photons from the hot plasma having energy > 7.1 keV, and the vacancies filled by either $2p$ (Kα line emission) or $3p$ (Kβ) electrons. The Kα lines have been observed in solar flare spectra by a number of high-resolution crystal spectrometers on spacecraft, notably those on *P78-1*, *S.M.M.*, and *Hinotori*. The much weaker Kβ line feature has been observed with the *Hinotori* spectrometer and more recently with the Bragg Crystal Spectrometer on *Yohkoh*.

Between wavelengths of about 1.85 and 1.89 Å are the strong lines of highly ionized iron which are emitted by the hot coronal flaring plasma, and include most notably the resonance line ($1s^2\,{}^1S_0 - 1s2p\,{}^1P_1$, called line w in the notation of Gabriel 1972) of the helium-like stage, Fe XXV (wavelength 1.850 Å), together with satellite lines formed by $1s - 2p$ transitions in the Li-like and lower ionization stages.

The intensity ratio of the Kα or Kβ lines to the Fe XXV w line is a function of the photospheric and coronal abundance of iron. Recent literature (e.g. Meyer 1985, Meyer 1992, and Feldman 1992) has suggested that the photospheric and coronal abundances of some elements are significantly different, with Meyer (1992) and Feldman (1992) stating that for elements (such as iron) with low first ionization potentials the coronal Fe/H abundance ratio is up to a factor of three larger than the photospheric Fe/H abundance ratio. In an analysis of the Kβ line data from *Yohkoh*, Phillips *et al.* developed a theory for the intensity ratio of the Kβ and Fe XXV w lines. The intensity ratio $I(\mathrm{K}\beta)/I(w)$ is only weakly dependent on the electron temperature T_e of the hot flaring plasma, but has a stronger dependence on the parameters describing the fluorescence of photospheric iron by the flaring plasma. These parameters include height of the flaring plasma h, and the heliocentric distance of the flare from sun centre θ. The ratio $I(\mathrm{K}\beta)/I(w)$ also depends on the photospheric-to-coronal iron abundance ratio, in an approximately proportional sense. The analysis of the *Yohkoh* Kβ data suggests that the coronal Fe/H abundance is equal to the photospheric to within approximately 30%, this result therefore differing from the conclusion of Meyer (1992) and Feldman (1992).

We have now extended the work of Phillips *et al.* (1994) to an analysis of the Kα lines as observed by the *S.M.M.* and *P78-1* X-ray spectrometers during flares. This is a preliminary report on the results obtained.

2. Observations

The Kα doublet at 1.936 and 1.940 Å was observed with the SOLFLEX instrument on the *P78-1* spacecraft and the Bent Crystal Spectrometer (BCS) on *S.M.M.*. The SOLFLEX instrument (Doschek, Kreplin, & Feldman 1979) consisted of four flat, Bragg-diffracting crystals which scanned small wavelength intervals back and forth by means of a stepping motor. Spectrometer I observed the iron lines mentioned above in the wavelength range 1.82–1.97 Å, using germanium crystal. For the observations used here a complete spectrum was scanned in a time of typically a minute. The Bent Crystal Spectrometer (BCS) on *S.M.M.* was described by Acton *et al.* (1980). *S.M.M.*'s lifetime was 1980 to 1989, but the pointed instruments including BCS were only operational in 1980 and again from 1984 to 1989. The BCS consisted of eight slightly curved germanium crystals which diffracted X-rays into position-sensitive proportional counters. A complete spectrum over the narrow wavelength intervals of each of the eight channels could be obtained in about 11 s, depending on the mode of operation. The Kα lines were observed by channel 2, the wavelength range of which was 1.928–1.945 Å, and the Fe XXV w line observed by channel 4, wavelength range 1.840–1.894 Å. Channel 2 operated only in the 1980 period. The Kα and Fe XXV w line intensities could be directly compared in the case of the *P78-1* SOLFLEX instrument since each was observed by the same spectrometer, but for the *S.M.M.* BCS, different channels were involved, and so cross-channel calibration factors were required. These were obtained from pre-launch measurements. For both the SOLFLEX and BCS instruments, there is a continuous background due to fluorescence radiation from the germanium crystals.

3. Results

A total of six flares were analyzed from the SOLFLEX data, with several spectra per flare. As the Fe XXV w and Kα lines were scanned at slightly different times in the development of each flare, time-profiles, consisting of count rates *vs.* time, were formed for each feature.

An average value of the count rate ratio of the Kα lines (Kα_1 and Kα_2 added together) to the Fe XXV w line was derived for each flare. Since the instrument sensitivity changes very little over this very small wavelength interval, the count rate ratio is essentially equal to the corresponding intensity ratio. Values of the heliocentric distance θ of each flare were obtained from the coordinates of the most obviously associated Hα flare.

For the *S.M.M.* data, the intensities of each of the Kα lines and the Fe XXV w line feature were derived by fitting Voigt profiles to the observed line profiles for a short period of time ($\sim$ 100 s) near the maximum of the Fe XXV w line intensity. Pre-launch intensity calibration factors were used to convert count rates to absolute intensities. Some 37 flares in 1980 were analyzed in this way. As before, the heliocentric distance θ of each flare was derived from Hα flare coordinates.

Figure 1 shows the observed intensity ratio for the *P78-1* flares (symbol $\diamond$) and the *S.M.M.* flares (+) plotted against heliocentric distance θ. For four of the *S.M.M.* flares, no Kα line emission could be detected above the fluorescence background, hence the observed ratio is zero.

Superimposed on Fig. 1 are calculated curves based on the theory given by Phillips *et al.* (1994) for the iron Kβ line feature. The ratio is actually the sum of the two Kα lines to the Fe XXV w line which is blended with numerous high-n dielectronic satellites that converge on the wavelength of the w line; their contribution was estimated from the atomic data of Bely-Dubau *et al.* (1982). As mentioned above, this ratio is in theory a function of θ and the height of the flare h, but only a weak function of temperature of the hot flaring plasma T_e. Three curves are shown for three different heights, $h = 0$, 7000, and 35 000 km. The theoretical dependence of the ratio on the photospheric-to-coronal Fe/H abundance is almost proportional, also as mentioned, but for the theory curves shown in Fig. 1, we made the *ad hoc* assumption that the photospheric Fe/H abundance ratio is equal to the coronal value. Note that the vertical axis applies to both observed points and calculated curves, i.e. the curves have not been shifted to fit the points.

As can be seen from this figure, there is very reasonable agreement between the observed points and curves shown. The six *P78-1* points are scattered between the theory curves for $h = 0$ and $h = 35\,000$ km. As this is probably a reasonable range of heights for the hot plasma emitting the Fe XXV line, much of the scatter is probably attributable to variations in flare heights. There is more scatter in the *S.M.M.* points, though they too are very close to the theory curves. Unlike the *P78-1* points, the intensity ratio of the Kα lines and w line involve a ratio of instrumental sensitivities, which as mentioned earlier were obtained from pre-launch measurements. An error in the latter could explain why the *S.M.M.* points do not match the theory curves as well as the *P78-1* points, though it would not explain the scatter.

There is slight evidence for a decreasing line ratio for flares near the limb ($\theta \approx 90°$). This would support the finding of Parmar *et al.* (1984) that the Kα lines are formed by fluorescence in the photosphere, since there is a fall-off in such emission for near-limb flares.

4. Conclusions

This preliminary analysis of flare-emitted photospheric iron Kα and Fe XXV w line intensities from *P78-1* and *S.M.M.* data supports the result of Phillips *et al.* (1994) from *Yohkoh* data, viz. that the photospheric Fe/H abundance is not significantly different from the coronal. The analysis relies on the fact, established by Parmar *et al.* (1984), that the Kα lines, like the Kβ line feature at 1.756 Å, are formed by fluorescence in the photosphere. This appears to be confirmed by the data discussed here, as well as the *Yohkoh* Kβ data discussed by Phillips *et al.* (1994).

The scatter in the *S.M.M.* points is not readily explained as yet, but it should be noted that a determination of the Fe/H abundance from *Yohkoh* BCS data using the intensity ratio of the Fe XXV w line to the continuum near the Ca XIX line at 3.177 Å by Fludra *et al.*

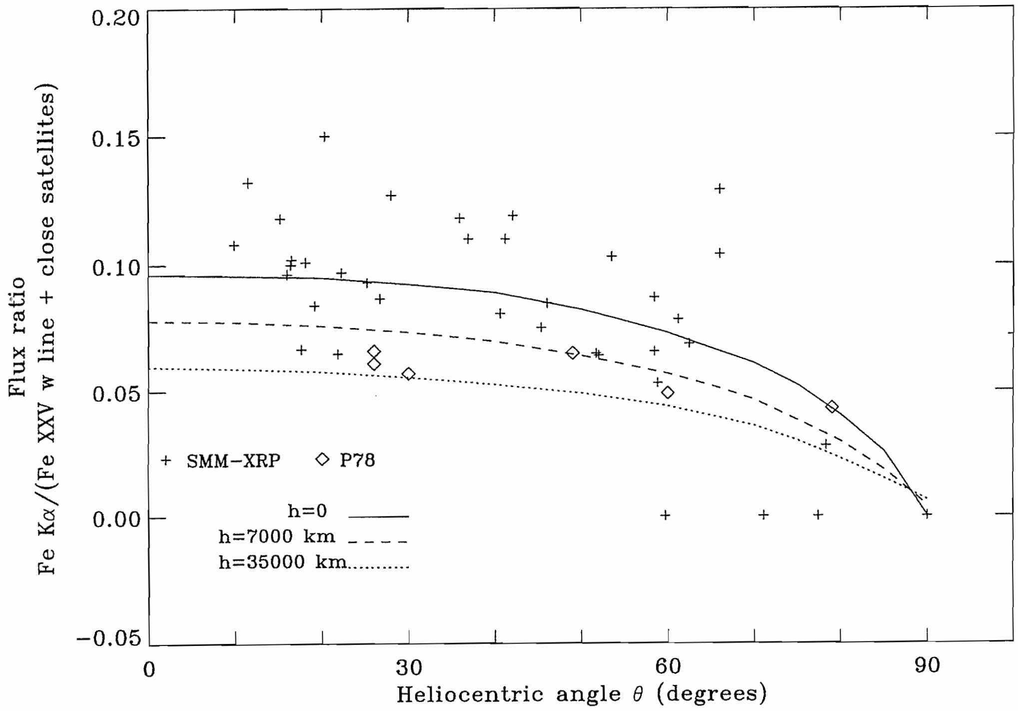

Fig. 1. —Flux ratio of the two Kα lines summed to the Fe XXV *w* line plotted for various flares against heliocentric angle θ. Flares observed by the *P78-1* SOLFLEX spectrometer indicated by + symbols, those by the *S.M.M.* BCS spectrometer by ◇ symbols.

(1993) shows a similar scatter. That work also gave a value of the coronal Fe/H abundance ratio that is consistent with the range of photospheric values obtained in the past few years.

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