Using high resolution solar X-ray spectra to benchmark the MEKAL spectral synthesis code

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ABSTRACT

With the upcoming launch of XMM with its high resolution spectrometer (RGS) onboard, it seems timely to review the accuracy of the spectral codes which will be used extensively. In this work, high resolution solar spectra have been used as a benchmark for the synthetic spectra derived from the MEKAL code. Improvements to the code have been implemented.

1. Introduction

The Reflection Grating Spectrometer (RGS) onboard the X-ray Multi-Mirror (XMM) observatory will provide high resolution spectroscopy ($\Delta\lambda \leq 0.05$ Å) in the wavelength range 5-35 Å. XMM will provide observations of a large range of non-solar sources. A number of sources like stellar coronae, clusters of galaxies and hot gas in interstellar and intergalactic medium are said to be in coronal ionization equilibrium.

As much of the line emission data, in particular the line wavelengths, are derived from atomic physics calculations, an observational *benchmark*, in which high-resolution spectra are compared with MEKAL synthesized spectra, is clearly desirable. Since a number of the sources to be observed with RGS are said to be in coronal ionization equilibrium, we can make use of high resolution solar spectra to benchmark the spectral synthesis codes.

Very high-resolution soft X-ray spectra have been obtained in the past using crystal spectrometers dedicated to solar active regions and flares. Among these are spectra from the Flat Crystal Spectrometer (FCS), part of the X-ray Polychromator which was on board the *Solar*

Maximum Mission spacecraft (*SMM*), which operated between 1980 and 1989. This paper is concerned with a benchmark study of the MEKAL code using solar flare spectra from the FCS instrument. Adjustments to the atomic code will be discussed in later sections.

2. Solar Flare Spectra

The *SMM* spacecraft operated fully for nine months in 1980, from the time of launch to the time when an attitude control unit on the spacecraft failed, and from 1984 when Space Shuttle astronauts repaired the attitude control unit to 1989 when the spacecraft re-entered the Earth's atmosphere. The wavelength coverage of the Flat Crystal Spectrometer (FCS) was 1.5–20 Å.

Despite operational problems, spectra taken on two occasions are suitable for analysis and comparison with MEKAL theoretical spectra.

Flare 1 : Flare 1 was during the decay of an **M3 flare** on August 25 1980. A single long spectral scan covering the full range of the FCS was performed, starting at 13:10 U.T. and lasting for approximately 20 minutes. There is significant line emission in the range 5–20 Å which is covered by four of the seven FCS channels. A large number of the lines in the 10.5–17 Å range are due to Fe ions, with the majority due to 2–3 transitions in ions in the range Fe XVII–Fe XIX.

Flare 2 : Several short spectral scans were made during a M4.5 flare on July 2 1985 between 21:19 U.T. and 21:41 U.T., which included the peak at about 21:25 U.T. Subsequently, much higher-excitation lines are apparent in these spectra, notably in the 7.8–10 Å range which includes intense 2–4 lines in various Fe ions (predominantly from Fe XIX to Fe XXIV).

The accuracy of relative wavelengths given by (Phillips et al, 1982) is less than 0.002 Å. Absolute wavelengths were obtained using a reference line in each of the seven channels, generally the resonance line ($1s^2\,{}^1S_0 - 1s2p\,{}^1P_0$) of He-like ions, the theoretical wavelengths of which were known to 0.001 Å or less.

3. Spectral Synthesis by MEKAL

Analysis of the soft X-ray and EUV spectra from non-solar astronomical sources in the past has generally made use of the several spectral synthesis codes that are available in the literature. The MEKAL code, used via the SPEX spectral software package (Mewe et al, 1995, Kaastra et al, 1996), has been one of the most frequently used of these, and contains a considerable amount of data relating to atomic transitions that give rise to both line and continuous spectra.

The original MEKA code (Kaastra & Mewe, 1993) was modified to allow for the fact that comparison of theoretical spectra with those observed by the *ASCA* spacecraft of the central regions of galaxy clusters (Fabian et al, 1994) showed a discrepancy with the intensity ratio of the two groups of spectral lines due to 3–2 and 4–2 transitions in various ions of Fe (specifically FeXVII–FeXXIV). The addition of more than 2000 lines in the in the 7–19 Å range using data from the HULLAC (Hebrew University/Lawrence Livermore Atomic Code) code (Klapisch et al, 1977) has enabled this discrepancy to be largely removed.

4. Reflection Grating Spectrometer

XMM is designed specifically to investigate in detail the X-ray emission characteristics of cosmic sources. The wavelength band of the Reflection Grating Spectrometer (RGS) is 5-35 Å (0.35-2.5 keV). It has a resolving power of $\geq$ 1000 which enables it to resolve the Fe L-shell FeXVII–FeXXIV line complex (10-18 Å), allowing more refined temperature diagnostics. The He-like O VII triplet allowed density diagnostics and velocity diagnostics from various Fe lines are permitted. Many of the lines in the Fe-L region are resolved emphasising the requirement for accurate wavelengths in the synthetic spectra.

5. Corrections to the Wavelengths

We used the SMM spectra to benchmark the MEKAL wavelengths. The wavelengths of lines which showed strong mis-matching were changed until the best χ^2 was achieved. The most extreme examples are listed in Table 1. Figure 1 shows the new fits to the solar spectra. Figure 2 shows how important these changes are for the analysis of XMM RGS spectra.

Most of the lines are fitted more accurately (e.g. the Mg XI forbidden line at 9.31 Å, which is blended with satellite lines j and k). This naturally produces a substantial change to the calulated DEM.

Table 1: Examples of the corrections to the wavelengths

Ion	λ_{orig} Å	λ_{corr} Å
Fe XVIII	11.761	11.741
Fe XVII	12.134	12.124
Fe XVII	12.274	12.264
Fe XVII	13.795	13.825
Fe XVII	15.272	15.265
Fe XVII	16.796	16.780
Fe XVII	17.071	17.055
Fe XVII	17.119	17.100

6. Conclusions

With relatively small wavelength adjustments, we have been able to achieve very good agreement between MEKAL and the solar flare spectra. This is particularly true of the Fe L-line

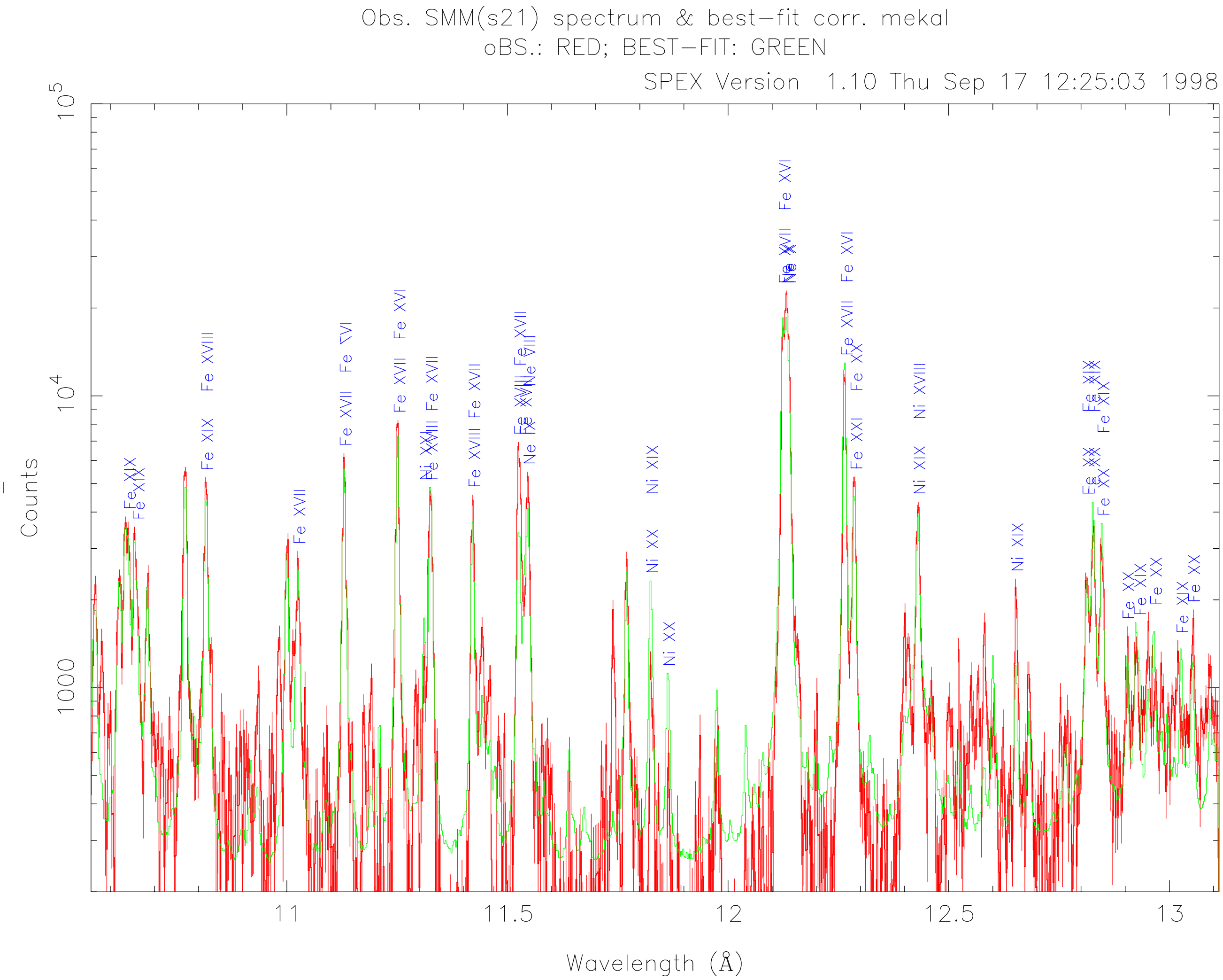

Fig. 1.— Figure showing the SMM solar flare spectra and the corrected fit using the new wavelengths

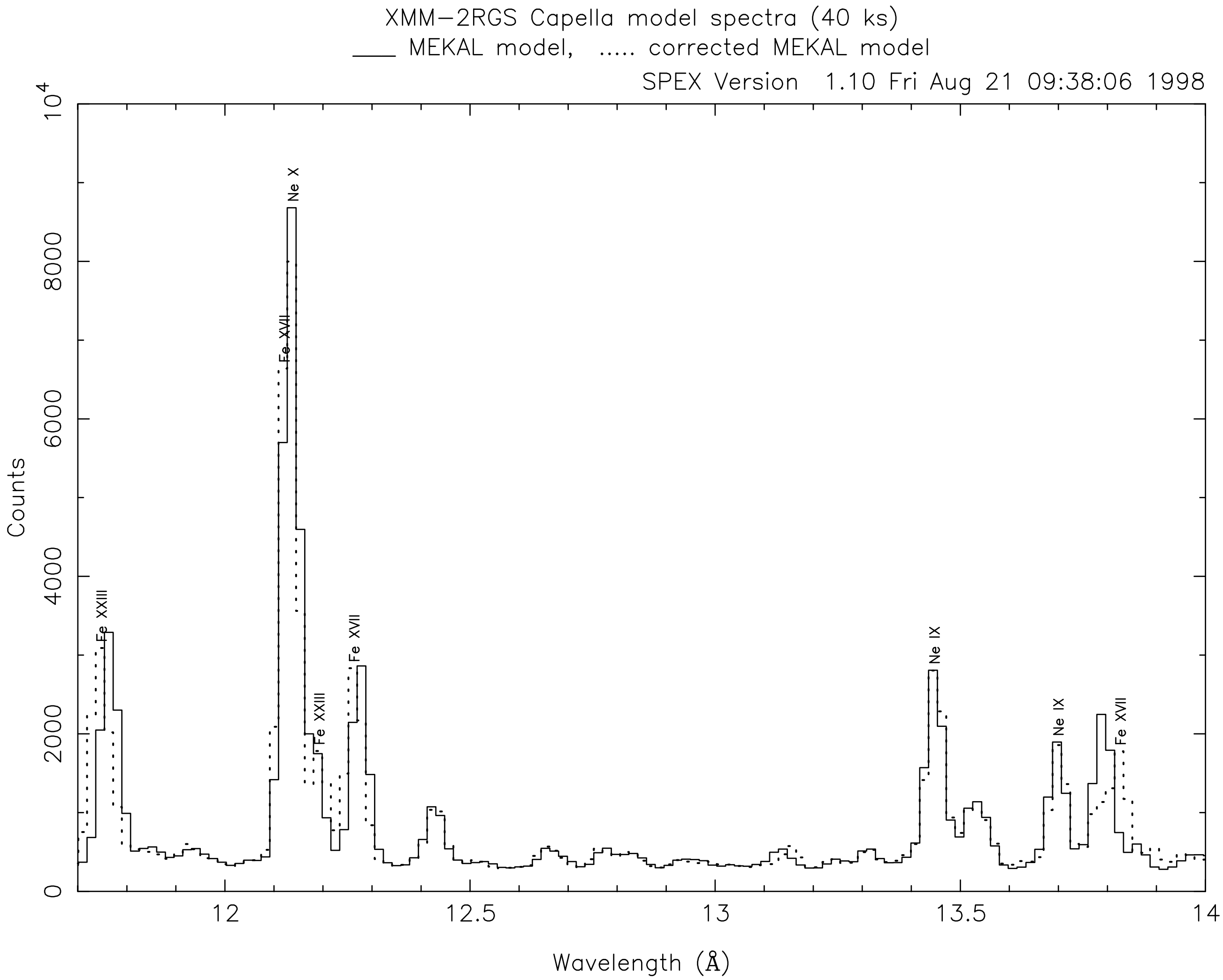

Fig. 2.— Figure showing the SMM solar flare spectra and the corrected fit using the new wavelengths

complex, where several Fe ions have $n = 2 - 3$ transitions that fall in the 10–14 Å (0.9–1.2 keV) region and Fe $n = 2 - 4$ lines (observed in the hot July 2, 1985 flare). When the comparison is completed, we shall have a very complete line list in the X-ray spectral region $1.9 - 20$ Å and the MEKAL code should give a very accurate representation of the X-ray spectra of sources in which excitation conditions (electron collisional excitation, radiative decay) are like those in solar flares.

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