Assuming equipartition of particle and magnetic-field energies implies a value of the magnetic field (at source radius $10^{13}$ cm) of 50 G and a relativistic electron energy density of $10^2$ erg cm$^{-3}$. The limits on source size and total energy restrict these quantities to within two orders of magntiude of their equipartition values.

More detailed analysis of the current data (including radiative-energy loss mechanisms, light crossing time, and free–free absorption by thermal particles) will allow a more stringent test of the model and a better constraint on the parameters. The velocity range and the minimum source size predict that the expansion of this source may be directly measurable with very long baseline interferometry (VLBI) techniques. By measuring the expansion velocity, VLBI observations would completely determine the physical parameters of the model.

If the apparent radio periodicity is supported by additional observations, the synchrotron emission region of Cyg X-3 is undergoing periodic particle injection. Periodic nonthermal radio emission has been observed from the much longer period binaries Cir X-1 (ref. 24), LS I+61°303 (ref. 25), and SS 433 (refs 26, 27), although the flaring mechanisms in those more widely separated systems are probably different. In the case of Cyg X-3, periodic production of relativistic particles may be a natural result of a surge in mass transfer (as suspected[26,27] for SS 433) at periastron passage in an eccentric orbit. The possible ~0.1-h difference between the radio and X-ray periods could arise from the beat between the 4.8-h orbital period and the possible 19-day period found from long-term timing studies of Cyg X-3 (ref. 28). The 19-day period is, in fact, consistent with apsidal motion of a binary orbit with an orbital eccentricity[28] of 0.03. A precise value for the radio period would, therefore, provide important information on the dynamics of the binary system itself.

The minimum size derived from our model is $60(M/M_{\odot})^{-1/3}$ binary radii, where $M$ is the total mass of the system and $M_{\odot}$ is the mass of the Sun. Hence the expanding synchrotron source model requires a mechanism for transporting energy from the binary system to the electrons in the outlying radio emission region. Vestrand's[22] suggestion of $\gamma$-ray interactions with outlying thermal material is possible, although bulk transport of energy in jets (as in SS 433) is perhaps more promising.

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# Variation in observed coronal calcium abundance of X-ray flare plasmas

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**Variations in chemical composition during solar flares have been inferred from elemental abundance changes in cosmic ray fluxes, but have so far not been detected spectroscopically. We present here the first spectroscopic evidence for the variation of the coronal calcium abundance in high-temperature solar flare plasmas. The analysed data consist of the high-resolution X-ray flare spectra ($\lambda/\Delta\lambda \approx 4{,}000$) observed with the Bent Crystal Spectrometer (BCS) on board the Solar Maximum Mission (SMM) satellite and described in detail by Acton *et al.*[1]. The observed abundance variation has important consequences for the analysis and interpretation of XUV and X-ray spectra.**

In its lowest energy channel the BCS observes the X-ray spectrum in the vicinity of the helium-like resonance, forbidden and intercombination emission lines of Ca XIX and the continuum, to the blue of the resonance line (see Fig. 1*b* in ref. 2). From BCS spectra we derive the line-to-continuum ratio ($I_L/I_C$) for the resonance line of Ca XIX ($\lambda = 3.1781$ Å) as a function of temperature.

We express the $I_L/I_C$ flux ratio as a function of electron temperature ($T$) for an optically-thin, isothermal plasma as:

$$\frac{I_L}{I_C} \propto A_{Ca} \frac{N_{Ca\,XIX}}{N_{Ca}} \frac{\Omega(T)}{G(T)} \qquad (1)$$

where $A_{Ca}$ is the calcium abundance relative to hydrogen, $\Omega(T)$ is the effective collision strength for the line emission (see ref. 3), and $G(T)$ is the generalized Gaunt factor describing the continuum emission (see ref. 4). $N_{Ca\,XIX}/N_{Ca}$, the concentration of the helium-like calcium ion relative to the total number of calcium ions, also depends on temperature.

An example of the observed $I_L/I_C$ evolutionary time behaviour during a flare is shown in Fig. 1 for the flare which occurred on 14 July 1980 at 08.25 UT. The electron temperature has been estimated from the ratio of the dielectronic satellite Ca XVIII $^2P_{1/2}$—$^2D_{3/2}$ ($\lambda = 3.208$ Å, line k in the notation of Gabriel[5]) intensity to the Ca XIX resonance line ($^1S_0$–$^1P_1$) intensity using the atomic data given by Bely-Dubau *et al.*[3]. This line ratio is a sensitive measure of the electron temperature and because the satellite is formed by dielectronic recombination, the accuracy does not depend on the assumed ionization balance calculation. The indicated $\pm 1\sigma$ error bars were estimated from the counting statistics of the resonance and satellite lines.

The observed $I_L/I_C$ evolution during the heating phase (*ab* in Fig. 1) shows a hysteresis behaviour with temperature that is not predicted by equation (1) which is single-valued for all values of temperature. The hysteresis of $I_L/I_C$ with temperature has been observed in several flares and three possible explanations are being investigated: the presence of a small amount (a few per cent of the total emission measure) of very hot plasma ($T > 10^8$ K); emission produced by non-thermal electrons; or a variation of the calcium abundance during the heating phase. Although a transiently-ionizing plasma could possibly give rise to the hysteresis of $I_L/I_C$ with temperature, the time of $\lesssim 10$ s to reach equilibrium for a typical density of $10^{10}$ cm$^3$ is much shorter than would be necessary to explain the observations.

Figure 2 shows the cooling phases (*bc* in Fig. 1) for the 14 July 1980 flare and for the flare which occurred on 29 June 1980 at 18.00 UT. During the cooling phase the temperature behaviour

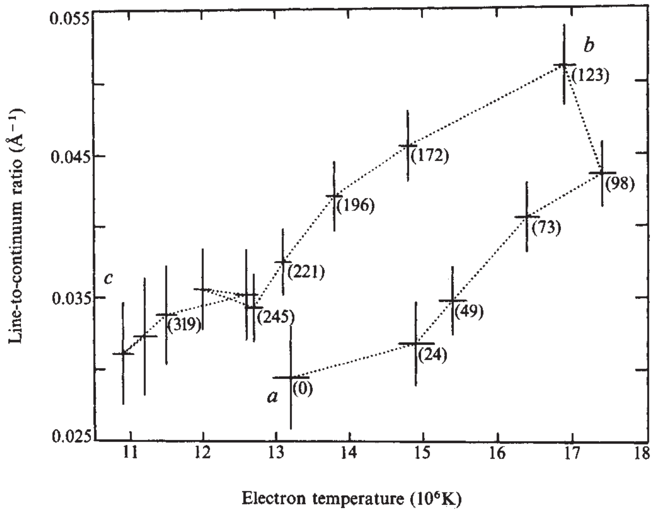

**Fig. 1** The line-to-continuum ratio ($I_L/I_C$) evolutionary time behaviour for the flare on 14 July 1980. Times in seconds after 8.24.35 UT are indicated in parentheses. The mean electron temperature has been estimated from the satellite-to-resonance line ratio (line k to line w in the notation of Gabriel[5]) using the atomic data given by Bely-Dubau *et al.*[3]. *ab* corresponds to the heating phase, *bc* to the cooling phase; $\pm 1\sigma$ error bars are indicated for the temperature estimations and $\pm 3\sigma$ error bars are indicated for the $I_L/I_C$ values.

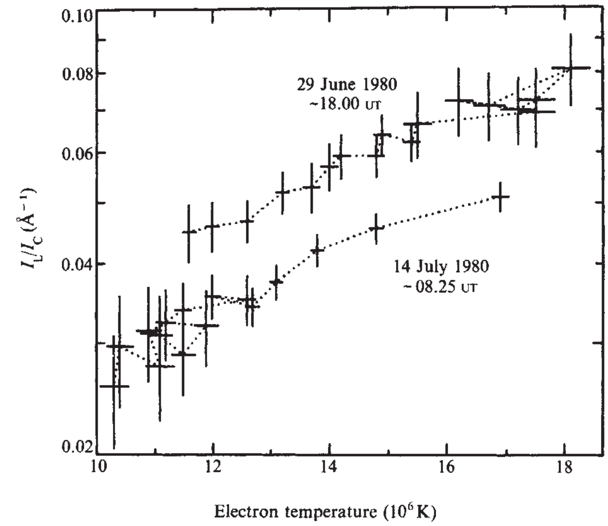

**Fig. 2** $I_L/I_C$ for cooling phases of two different flares. The error bars are as in Fig. 1. The constant vertical shift corresponds to a variation in the calcium abundance by a factor of 1.4.

of $I_L/I_C$ had the same form for 13 flares we considered, except that the normalization factor varied by as much as 2.5 between flares in extreme cases. This observed variation in the normalization factor is probably due to the different coronal calcium abundance in each flare. We have ruled out multi-thermal effects as the cause of the observed variation in the normalization of $I_L/I_C$ during the cooling phase. As all the factors in equation (1) apart from the abundance depend on atomic physics and are thus not expected to vary, we are left to conclude that we have observed for the first time a flare-to-flare variation of the coronal calcium abundance.

The BCS continuum fluxes were checked by comparison with observations obtained with the broad-band Hard X-Ray Imaging Spectrometer[6] (HXIS), on the SMM spacecraft. Preliminary work carried out on HXIS data has shown a similar hysteresis behaviour with temperature for the ratio of the measured-to-predicted count rate for channel 2 (5.5–8.0 keV). In this energy band there is a contribution of ~30–50% from Fe $K\alpha$ line radiation and thus the observed behaviour may be attributable to variations in the iron elemental abundance. If proven, these observations could provide spatial information concerning the elemental composition distribution.

Following theoretical considerations[7,8] that thermal diffusion could have a significant role in differentiating the elemental abundance structure inside the Sun, several authors have investigated theoretically the role of this effect on the composition of the upper solar atmosphere. It has been predicted[9–11] that a layer should exist within the transition region where the heavy elemental abundances (relative to hydrogen) should be increased by a significant factor—sometimes much greater than 10—but to date there has been no observational evidence[12,13] confirming these results. The only positive detection of varying elemental composition of the solar-originated plasma has been found in solar wind composition measurements[14] (depletion of helium, enrichment of heavier elements in the post-flare-associated shocks) and in observations of the middle-energy, solar cosmic rays[15] (enrichment of heavier elements proportional to atomic weight).

The observed variation (see Fig. 2) in the calcium abundance for different flare plasmas could be attributed to: (1) variations in the elemental composition of the pre-flare plasma or (2) variations in the speed of the elemental separation process during flare heating. The fundamental process providing the basis for any elemental separation is probably differential diffusion occurring across steep temperature and pressure gradients. Detailed considerations of the role of diffusion in cases (1) and (2) will be given elsewhere.

The calcium abundance variation probably represents the first spectroscopic observation of a change in the flare plasma chemical composition. This discovery has important consequences for the analysis of flare spectra in the X-ray region and at longer wavelengths. Many diagnostic techniques rely on the assumption that the abundance of a given element is constant or that the relative chemical composition is constant in time and space in the solar corona. This assumption will now have to be reconsidered. For example, differential emission measure analysis may be affected, as well as temperature and density line ratio diagnostics which rely on lines belonging to different elements. It is possible that the relative chemical composition of heavier elements is not altered significantly from flare to flare, but this needs to be verified experimentally.

The potential of abundance variation analysis as a method of transition-region diagnostics will probably stimulate future observing programmes. The chemical composition should be considered as an additional parameter for characterizing the flare plasma.

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