Helium-Like Sulphur Emission Lines in Solar Active Regions and Their Sub-C Class Variability

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Abstract

Helium-like sulphur spectra (formation temperature, $T_{\text{in}} \sim 18 \times 10^6$ K) from coronal active regions are being obtained by the Bragg Crystal Spectrometer onboard the Yohkoh mission. The average electron temperatures of the quiescent active regions deduced from the full-disk integrated sulphur spectra are 3.5–4.1 $\times 10^6$ K. The temporal behavior of the emission lines in the sub-C level events shows that hot plasmas ($T > 10^7$ K) can be produced in these weak events.

Key words: Helium-like sulphur lines — Sun: activity — Sun: corona — Sun: spectra — Sun: X-rays

1. Introduction

Due to its high sensitivity, the Bragg Crystal Spectrometer (BCS) onboard the Yohkoh mission is capable of detecting sulphur emission lines from quiescent active regions despite their high formation temperature of $18 \times 10^6$ K (Mewe et al. 1985). During the last decade, several attempts were made to diagnose active regions using high-resolution soft X-ray spectra. The Flat Crystal Spectrometer (FCS) on the Solar Maximum Mission (SMM) succeeded in mapping the temperatures and emission measures, as well as the nonthermal line broadening of active regions (Saba and Strong 1991). McKenzie (1987) analyzed the SOLEX spectra and reported the differential natures of the temperature distributions in active regions. Differential emission measures of the active regions were also obtained by Skylab instruments (Webb 1981). The BCS has a field of view covering nearly the entire solar disk and its increased sensitivity in the sulphur channel allows observations of active regions with much higher cadence. In this paper we describe the characteristics of the helium-like sulphur lines from active regions and their temporal variations.


The period of 1992 March 11–13 was one of the intervals since the launch of Yohkoh when solar activity was extremely low. The quiescent level of GOES X-ray flux (1–8 Å) was below C1 (Preliminary Report and Forecast of Solar Geophysical Data, SESC PRG 863, 1992), and only a few small events were recorded during these three days. The largest of these was a C7.8 flare at the beginning of March 11. The BCS was able to detect the helium-like sulphur lines from quiescent active regions and related brighter events. The intensity fluctuations of the S X V emission lines were generally better correlated with the GOES 0.5–4 Å intensities than with those in the 1–8 Å wavelength band.

Regarding an event on March 12 in NOAA region 7099, figure 1 shows the light curves of the helium-like sulphur resonance line, w, and a blended feature consisting of the forbidden line, z, of the helium-like ion, and the lithium-like dielectronic satellites, j and k. The letter notation follows Gabriel (1972). This event was noted as B9.6 in the GOES event list (Preliminary Report and Forecast of Solar Geophysical Data, SESC PRG 863, 1992). The BCS recorded the peaks of twenty similar small events during this period.

The total count rate of the entire sulphur spectrum in the quiescent state was about 80 cps, and the detector
background noise level was less than 10 cps. The peak total count rate during this event was 247 cps. Sulphur spectra were obtained every 3 s when the spacecraft was operating at the high telemetry rate, and every 24 s at the medium rate (see Culhane et al. 1991).

The upper sulphur spectrum in figure 2 was taken before the onset of a flare. The observed line broadening results from the extended spatial distribution of several active regions on the solar disk. The BCS spectrometers are oriented so that the dispersion directions of the spectrometers approximately coincide with the North-South (N-S) axis of the Sun. Since X-rays from different N-S locations on the Sun enter the BCS at slightly different Bragg angles, several simultaneously emitting regions distributed in the N-S direction will have a broad apparent line width, while a single small, but dominant, emitting region will have narrower lines, unless the lines are intrinsically broad.

The S XV spectra have been analyzed using spectral fitting programs written for the BCS based on a method described by Fludra et al. (1989) (see also Culhane et al. 1992). To generate the theoretical S XV spectra, we used the atomic data for dielectronic satellites from J. Dubau (1992, private communication) and helium-like line ratios of McCann and Keenan (1988). A single temperature fit has been applied to the spectrum in order to reveal the average characteristics. The derived temperature was about $3.9 \times 10^6$ K, and the emission measure was $4.7 \times 10^{48}$ cm$^{-3}$. It is noted that the observed line profiles deform according to the intensity distribution of the active regions, and are not ideally fitted to the theoretical single-temperature spectrum. Therefore, the derived emission measure might be subject to this error, though in the present case, the deformation of the line profiles are not so significant as can be seen in figure 2. The best-fit theoretical spectrum is indicated by the solid line in the figure. Temperatures of $3.5-4.0 \times 10^6$ K were obtained from the spectra during this quiescent period. The temperature from the S XV diagnostic ratio is weighted by the plasma emission measure as a function of the temperature (differential emission measure); it is also weighted by the S XV line emissivity, which is a rapidly increasing function of the temperature. It is therefore thought that for the deduced average active region temperature, greater weight is given to the contribution from the higher temperature regions of the plasma.

Fig. 1. A B9.6 flare, 1992 March 12, 1426 UT. Light curves of the resonance line, (solid line), the blend of forbidden line (z) and dielectronic satellites (j and k) (dotted line) and the intensity ratio of the blended feature (DS) to the resonance line (R), which is the temperature diagnostic.
in active regions. McKenzie (1987) used the O VII, Ne IX, and Mg X line spectra of the SOLEX experiment on P78-1 and found that the temperatures of active regions are in the range 1.7–2.4 (1.2–1.6) \times 10^6 K (O VII), 2.2–3.8 \times 10^6 K (Ne IX), and 3–6 \times 10^6 K (Mg X). Lang et al. (1987) obtained a temperature of 3 \times 10^6 K for the active regions using the SMM FCS spectra (O VIII and Mg X line ratios). Saba and Strong (1991) used six line ratios observed by the FCS to derive T \sim 3 \times 10^6 K consistently. These temperatures are plausible for the hottest part of the active regions and are consistent with the high end of the Skylab observations (Webb 1981), and with the Yohkoh soft X-ray observations (Hara et al. 1992). The results are also consistent with the temperature and emission measure derived from the GOES monitors (Thomas et al. 1985), though it is slightly outside the range of reliable polynomial fits (Bornmann 1990).

The sulphur emission spectrum changes with time as the activity varies. More than twenty events were observed during the three days of BCS observations, some of which were not identified in the GOES event list. In figure 1, the total count rates in the resonance line and in the blend at 5.1 Å are plotted against time, with the continuum background intensity in the lines being subtracted. The line ratio of the two lines is shown in the lower panel of figure 1, and is sensitive to the electron temperature (McCann and Keenan 1988). Pre-flare, the ratio was about 1.3–1.5, which corresponded to T_e \sim 3.5–4 \times 10^6 K. It fell to 0.67 when the flare attained its maximum temperature. The integrated spectrum at the temperature maximum in figure 2 gives a temperature of 6.4 \times 10^6 K and an emission measure of 1.6 \times 10^{48} \text{ cm}^{-3}. The decrease in the emission measure during the flare can be understood if we recognize that the significant background sulphur emissions arise from large areas outside the flaring region (Bornmann 1990); it can thus be quite inaccurate to estimate the preflare emission measure of the flaring plasma using detectors having a full sun field of view. In such cases, the derived value of the temperature will be less than the actual temperature of the flaring plasma. It is worth noting that some of the events in the GOES B-class have the time of maximum intensity delayed relative to that of maximum temperature.

Simultaneous observations of flaring plasmas and quiescent active regions affect the derived parameters of plasmas, as shown in figure 3, where the peak intensity of the resonance line is plotted against the minimum line
Fig. 3. S xv resonance line intensities are plotted against the minimum line ratio for temperature diagnostics. The solid line indicates the locations of events in the diagram expected from a simple two-component model. The intensity and line ratio of the quiescent background are assumed to be 24 and 1.5 cps, respectively. The line ratio of the flaring components of all intensities is assumed to be 0.45.

ratio for the events observed during the three-day period. The minimum line ratio for the temperature diagnostic of an M1.9 flare (1992 January 5, 1315 UT) plotted in the figure is 0.45, which gives an electron temperature of $16 \times 10^6$ K. This value of 0.45 is in good agreement with the calculated ratio of MaCann and Keenan (1988). This ratio becomes insensitive to temperature above the point of maximum emissivity, $T_m \sim 18 \times 10^6$ K (Mewe et al. 1985). The solid line in the figure indicates a primitive two-temperature model. It was assumed that the background resonance line from the quiescent active regions has an intensity of 24 cps, a line ratio of 1.5, and that the line ratio at the peak of all events is 0.45. The data points of each event in the diagram also closely follow the curve. The reasonable fit of this simple model suggests that the contribution of quiescent active regions affects the analysis of the S xv spectra of flaring solar plasmas, and that sub-C level events could produce high-temperature ($T > 10^7$ K) plasmas. However, the line ratios indicate apparently lower temperatures in a single-temperature fit. This was also confirmed by the temperature derived from the simultaneous BCS Ca xix spectrum ($T_{Ca} \sim 12 \times 10^6$ K). It is clear that the Ca xix spectra, being emitted by hotter and more compact plasmas, are generally much less affected by quiescent active region contributions. However, the Ca xix spectral coverage chosen for BCS does not include the full diagnostics range, and the electron temperatures were estimated from the ratio of the resonance line to the weak blend of $n = 3$ lines.

It is difficult in the sulphur spectra of these weak events to see the blueshifted component or the blue asymmetry which is sometimes seen in large flares. These components tend to be hidden in the broad line wings caused by quiescent active regions. However, it is clear that no strong blue asymmetries were seen in the resonance line during the rise phase of these events. A possible exception is an event at 1992 January 17, 0144 UT, which seemed to have a strong blueshifted component corresponding to a velocity of 250–350 km s$^{-1}$ in the resonance line before the stationary component became dominant. The temporal behavior of the line profiles was quite similar to that observed in the Fe xxv resonance line in the X12 event of 1982 June 6 (Watanabe 1990). The frequent occurrence of weak events in an active region continually makes loop densities in the active region that are much
higher than the average coronal density and could suppress violent plasma motions in less energetic events.

3. Summary

Helium-like sulphur lines in solar active regions were observed by Yohkoh BCS during a period in 1992 March, when solar activity was rather low. Synthetic spectral analysis gives a representing temperature of 3.5–4 × 10^6 K for all active regions on the solar disk. The line widths were broad because of the distribution of active regions in the direction of the spectrometer dispersion. The spectrum at the peak of a B9.6 flare showed a temperature of 6.4 × 10^6 K and an emission measure about one third of the preflare state. Together with the other twenty events observed during this period, this implies that the maximum temperature of the flaring plasma could be above 10 × 10^6 K, higher than the apparent temperature deduced from synthetic spectral fitting. The production of a hot thermal plasma takes place even in the GOES B-class events. Further, some of the events show the maximum intensity delayed relative to the maximum temperature, which is also common in solar flares and is indicative of the involvement of a nonthermal heating process in these events.

Tiny events occurring frequently in the active regions would raise the scenario of episodic coronal heating and nano-flares (Parker 1988; Sturrock et al. 1990). SXT images identified these events as being the brightenings of active region loops (Shimizu et al. 1992). SXT imaging observations are proving to be indispensable for an accurate BCS spectral analysis.

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