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High-resolution X-ray spectra of solar flares

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Abstract

I discuss high-resolution solar flare soft X-ray spectra and also comment on some recent results from extreme ultraviolet (EUV) spectroscopy. Spectra of solar flares at these wavelengths have been recorded since the late 1960s, beginning primarily with the NASA Orbiting Solar Observatory (OSO) series of spacecraft. Knowledge of EUV flare spectra took a quantum leap with the NASA Skylab Apollo Telescope Mount spectrographs in the early 1970s. Knowledge of the X-ray spectrum took a similar leap in the 1980s with the US Department of Defense P78-1 spacecraft, the NASA Solar Maximum Mission spacecraft (SMM), and the Japanese ISAS Hinotori spacecraft. Investigations of flare X-ray spectra continued with the Bragg Crystal Spectrometer (BCS) experiment on the Japanese Yohkoh mission. EUV solar flare spectroscopy has been extended with the Solar Ultraviolet Measurements of Emitted Radiation (SUMER) spectrometer and the Coronal Diagnostics Spectrometer (CDS) on the ESA Solar and Heliospheric Observatory (SOHO) spacecraft. Recently, more Bragg crystal spectra have become available from experiments such as the RESIK spectrometers on the Russian Coronas-F spacecraft. In addition to the above missions, significant earlier contributions were made with instrumentation on a number of other spacecraft, e.g., the Soviet Intercosmos X-ray spectrometers. Our knowledge of the physical conditions in solar flares has been greatly expanded from analyses of X-ray and EUV flare spectra. I discuss the general characteristics of the flare emission line and continuum spectra, and the physical processes that produce them. I summarize what we have learned about solar flares from the spectra, and highlight a few problems and prospects for future solar flare research.
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Keywords: Solar flares; X-ray spectra; EUV spectra

1. Introduction

The purpose of this paper is to provide a brief review of the highlights of high-resolution X-ray spectroscopy of solar flares for solar researchers unfamiliar with the field, and for current researchers involved with CHANDRA and XMM/Newton research. There are many similarities between solar flare spectra and the spectra of certain other astrophysical sources, such as stellar coronae and supernovae remnants. This statement can be generalized to state that solar flare spectra have at least some strong similarities to any cosmic spectra obtained from a source in which the ion populations are primarily determined by collisional ionization and recombination, and in which the ion level population mechanism is primarily electron collisional excitation. The similarities are less for sources for which the ion populations are determined primarily by photoionization, or obviously for sources for which the gravitational field is a major player in line profile formation.

In this paper, I will discuss the solar flare X-ray/EUV spectrum, the atomic processes responsible for producing the lines and continuum, what solar flare researchers have learned about flares from the spectra, and finally some unresolved problems for future research.

2. Solar flare data sets

Solar flare X-ray spectroscopy has been an active field of research since the dawn of the space age. Initially, all spectra were broadband low-resolution

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spectra, i.e., ion chamber or proportional counter spectra. In the late 1960s, Bragg crystal spectrometers began to be flown and these reached their spectral resolution pinnacle during the 1980s. Unfortunately, the spatial resolution of these spectrometers was either zero (uncollimated) or no better than about 10″, which solar flare researchers now realize is inadequate for understanding anything but the coarsest morphology of a spatially large flare. Furthermore, the spectral resolution of these spectrometers was limited due to the use of mosaic crystals such as LiF, EDDT, and KAP.

The launch of the Skylab manned space station in 1973 resulted in spectral imaging of flares in the EUV with about 2″ spatial resolution and also very high spectral resolution. Unfortunately, due to the use of film as a detector, and the flight of Skylab at a time near solar minimum, the spectral flare data sets from Skylab are limited in temporal resolution and by sensitivity.

In the 1990s, Bragg spectrometers were flown on the Yohkoh spacecraft along with a grazing incidence X-ray telescope and a hard X-ray imaging telescope. But because the spectrometers were uncollimated, it was difficult to understand the relationship of many aspects of the spectra with respect to the flare images. Also flown in the 1990s were the still-operating TRACE normal incidence EUV telescope, and the still-operating SUMER and CDS EUV/UV spectrometers flown on the SOHO spacecraft. TRACE does not have high-resolution spectroscopic capability and SUMER and CDS, while having high spectral resolution, can only obtain spectral images with rather low time resolution. Furthermore, the data rate from the SOHO spacecraft is too low for very high time resolution flare observations. The first solar instrument to have both high spatial and spectral resolution capability along with high time resolution will be the EIS spectrometer on Solar-B, currently scheduled for launch in August, 2006 (see Culhane et al., 2005).

More details about some of the solar flare missions are briefly summarized below:

Orbiting Solar Observatories (OSO) era (1960s): coarse resolution Bragg crystal spectrometers, EUV imaging spectrometers, Bragg crystal rocket experiments, wavelength windows from about 1 to 400 Å.

Skylab Space Station (1973–1974): NRL S082-A slitless spectroheliograph – monochromatic EUV flare images between about 170 and 630 Å (Fe XXII–Fe XXIV), 2″ spatial resolution; AS&E and MSFC grazing incidence X-ray telescopes – a few arcseconds spatial resolution; all instruments used film as a detector.

P78-1, *Solar Maximum Mission (SMM)*, *Hinotori* (~1980s): high-resolution Bragg crystal X-ray spectrometers – high spectral but zero or poor spatial resolution; Hinotori hard X-ray imager – about 10″ spatial resolution; SMM hard X-ray imager – about 8″ spatial resolution, wavelength coverage was in selected bands between about 1 and 25 Å.

Yohkoh (1991–2001): grazing incidence X-ray telescope (SXT) – ~5″ spatial resolution, CCD detector; hard X-ray imaging telescope (HXT) – about 5″ spatial resolution; Bragg crystal spectrometers – high spectral but no spatial resolution, wavelength coverage was in four narrow wavelength windows centered on He-like Ca XIX, S XV, Fe XXV, and H-like Fe XXVI.

SOHO (1995+): normal incidence EUV telescope in four narrow wavelength bands centered near He II (304 Å), Fe X (170 Å), Fe XII (195 Å), and Fe XV (284 Å). EUV slit spectra – highest spatial resolution spectra are 1″ spatial resolution along slit; about 170–1610 Å; lower transition region, corona, Fe XVII–Fe XXIII.

TRACE (1998+): EUV multilayer telescope – 0.5–1″ spatial resolution; Fe XXIV, coronal, and transition region flare images. TRACE covers narrow wavebands centered on 171 Å Fe IX, 195 Å Fe XII, 284 Å Fe XV, 1216 Å H I, 1550 Å C IV, and the 1600 Å continuum.

Coronas-F (2001+): X-ray spectrometers and imaging telescopes; RESIK has four spectrometer wavebands between 3.3 and 6.1 Å; includes the K shell Fe and Ni complex through third-order diffraction.

Solar-B (2006+): EUV Imaging Spectrometer (EIS) – 170–210 Å, 250–290 Å, 2″ spatial resolution, 0.0223 Å/pixel, slits and slots, He II, coronal lines, Fe XXIII, Fe XXIV.

Specific references to the above instrumentation are too numerous to list here. References may easily be found via the web.

3. The solar flare spectrum

The solar flare X-ray spectrum between about 1 and 25 Å consists primarily of H-like and He-like emission lines of solar abundant elements, so-called "satellite" lines associated with the H-like and He-like lines and produced by dielectronic capture followed by radiative stabilization, and a free–free and free–bound continuum. (Some satellite lines are also produced by electron impact excitation.) There are no absorption lines, and electron impact excitation is the primary excitation mechanism for lines other than dielectronic satellite lines, although both radiative and dielectronic recombination can make significant contributions to some He-like and H-like lines and to Fe XVII lines. Examples of solar flare X-ray spectra at the longer wavelength end of this region are given in Phillips et al. (1982) and McKenzie et al. (1980). Photoexcitation is only important for the Fe Kα lines near 1.93 Å. These lines are produced by fluorescent photospheric emission caused by the X-ray flare radiation in the overlying coronal flare loops. The Fe Kα lines are seen weakly in solar flare disk spectra but are absent in limb spectra due to the small cross-section of the