Future Prospects for Solar EUV and Soft X-ray Spectroscopy Missions

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ABSTRACT

Future prospects for solar spectroscopy missions operating in the extreme ultraviolet (EUV) and soft X-ray (SXR) wavelength ranges, 1.2–1600 Å, are discussed. NASA is the major funder of Solar Physics missions, and brief summaries of the opportunities for mission development under NASA are given. The methods of observing the Sun in the two wavelength ranges are summarized with a particular focus on imaging spectroscopy techniques. The major spectral features in the EUV and SXR regions are identified, and then the upcoming instruments and concepts are summarized. The instruments range from large spectrometers on dedicated missions, to tiny, low-cost CubeSats launched through rideshare opportunities.

Keywords: keyword, keyword, keyword, keyword, keyword, keyword, keyword, keyword

1 INTRODUCTION

This paper discusses prospects for future extreme ultraviolet (EUV) and soft X-ray (SXR) spectroscopic missions observing the Sun. It is based on presentations given by the author at the 2018 American Geophysical Union meeting and the 2019 RHESSI Workshop.

The EUV and SXR contain a huge number of narrow emission lines from many different elements and ion species formed in all layers of the solar atmosphere, and spectroscopy plays a critical role in understanding the physics occurring there. Doppler shifts yield true plasma velocity measurements, while broadening of the lines beyond the known thermal and instrumental broadening can yield information about turbulence, wave propagation or non-equilibrium processes. Modeling of the atomic processes occurring in the atmosphere is necessary to uncover emission line ratio diagnostics for individual ions that can yield the plasma temperature and density. The CHIANTI atomic database (Young et al., 2016) is widely used in Solar Physics for modeling emission lines. Combining lines from multiple ions and elements allows the differential emission measure—a quantity that describes the amount of plasma at different temperatures—to be obtained, and the ratios of element abundances. The latter is important for understanding the so-called “FIP effect”: a phenomenon in the corona and solar wind whereby elements with low first ionization potentials (FIPs) are found enhanced over those with high FIPs (Laming, 2015). A detailed review of EUV and SXR spectroscopic diagnostics is given by Del Zanna and Mason (2018).

The article is organized as follows. Since most solar missions are funded by NASA either through NASA-led projects, or as contributions to non-US missions then Sects. 2 and 3 give details about the Heliophysics program at NASA and the mission opportunities that are available. Sect. 4 defines the wavelength regions...
Table 1. Mission and instrument acronyms used in this work. The launch year in brackets is given where appropriate.

| Mission / Instrument Acronym | Description / Year(s) |
|------------------------------|------------------------|
| CDS | Coronal Diagnostic Spectrometer (1995) |
| COSIE | COronal Spectrographic Imager in the Extreme ultraviolet |
| CubIXSS | CubeSat Imaging X-ray Solar Spectrometer |
| DAXSS | Dual Aperture X-ray Solar Spectrometer |
| EIS | EUV Imaging Spectrometer (2006) |
| EIT | EUV Imaging Telescope (1995) |
| ESIS | EUV Snapshot Imaging Spectrograph (2019) |
| EUNIS | Extreme Ultraviolet Normal Incidence Spectrograph (2006,07,13) |
| EVE | Extreme ultraviolet Variability Experiment (2010) |
| FOXSI | Focusing Optics X-ray Solar Imager (2012,14,18) |
| FURST | Full-Sun Ultraviolet Rocket Spectrograph |
| Hi-C | High-resolution Coronal Imager (2012,18) |
| IRIS | Interface Region Imaging Spectrograph (2014) |
| LEMUR | Large European module for solar Ultraviolet Research |
| MaGIXS | Marshall Grazing Incidence X-ray Spectrometer |
| MinXSS | Miniature X-ray Solar Spectrometer (2016,18) |
| MUSE | MULTI-slit Solar Explorer |
| NIXT | Normal Incidence X-ray Telescope (1989–93) |
| RDS | Rotating Drum x-ray Spectrometer |
| RHESSI | Reuven Ramaty High Energy Solar Spectroscopic Imager (2002) |
| SERTS | Solar EUV Rocket Telescope and Spectrograph (1989–99) |
| SOHO | Solar and Heliospheric Observatory (1995) |
| SPICE | Spectral Imaging of the Coronal Environment (2020) |
| SSAXI | SmallSat Solar Axion and Activity X-ray Imager |
| STIX | Spectrometer / Telescope for Imaging X-rays (2020) |
| SunCET | Sun Coronal Ejection Tracker |
| SUVI | Solar Ultraviolet Imager (2016,18) |
| SWAP | Sun Watcher with Active Pixel System detector and Image Processing (2009) |
| UVCS | Ultraviolet Coronagraph Spectrometer (1995) |
| VERIS | VEry high Resolution Imaging Spectrograph (2013) |
| VISORS | VIrtual Super-resolution Optics with Reconfigurable Swarms |

Many acronyms are used in this article for the names of instruments and missions and so a summary is given in Table 1.

2 STRUCTURE OF NASA HELIOPHYSICS

Heliophysics is one of the four science sub-divisions within the NASA Science Mission Directorate (SMD), with the others being Astrophysics, Planetary Science and Earth Science. For financial year FY20, the total NASA budget was $23B with SMD receiving $7B. Heliophysics has the smallest budget of the four science divisions, receiving $725M in FY20. Within Heliophysics, there are five main science areas: Solar Physics, Heliospheric Physics, Space Weather, Geospace Physics and Ionospheric, Thermospheric and Magnetospheric (ITM) Physics. The present article is specifically about Solar Physics missions. New Heliophysics missions are launched with a frequency of 1–2 years, with the most recent being the
Ionospheric Connection Explorer (ICON) in 2019 and the Parker Solar Probe (PSP) and Global-scale Observations of the Limb and Disk (GOLD) missions in 2018.

3 NASA MISSION OPPORTUNITIES

NASA missions broadly fall into three categories:

1. PI-led. These are competitively-selected missions led by a Principal Investigator, usually through the NASA Explorer program. Examples include IRIS and RHESSI.

2. Strategic mission. These missions are directed by NASA, and led by a PI at a NASA center. Individual instruments on the mission are competed and led by institute PIs. There are two types of strategic mission: Solar-Terrestrial Probes and Living With a Star (LWS) missions. SDO is a LWS mission, andSTEREO andHinodeare STP missions, the latter led out of NASA-Marshall and the others out of NASA-Goddard.

3. Mission of Opportunity (MOO). These are cheaper missions and can be selected in combination with a larger mission, as part of foreign partner mission, or as an International Space Station mission. Examples include EUVST and GOLD.

The process for selecting PI-led missions and MOOs typically follows the pattern of a Call for Proposals, a review followed by a down-select, funded Phase A studies for the advancing mission concepts, followed by a final selection. The time between proposal submission and final selection can be up to two years.

The NASA Explorer program funds Small and Medium Size missions, referred to as SMEX and MIDE, respectively, with budgets of around $150M and $250M. The most recent solar SMEX missions selected by NASA were IRIS in 2009 and PUNCH in 2019, and the next Call for Proposals is expected in the 2021–2022 time-frame. The two most recent MIDE missions were ICON, selected in 2013 and launched in 2019, and THEMIS, selected in 2003 and launched in 2007. Neither of these are Solar Physics missions, however. A MIDE Call for Proposals was released in 2019, with five missions selected for Phase-A studies in 2020. One of these, MUSE, is discussed below.

In addition to the above opportunities, NASA also has options for smaller-scale projects to be flown on sounding rockets and balloons. CubeSats and SmallSats are increasingly common and are typically launched through “rideshare” arrangements to minimize costs. NASA also funds instruments to be placed on the International Space Station but this has not been used for solar EUV and SXR experiments so far.

4 X-RAY AND EUV WAVELENGTH REGIONS

For the purposes of this article, we take an unconventional definition of the soft X-ray (SXR) region to be between 1.2 and 50 Å and the EUV to consist of two regions: between 50–500 Å (EUV-A) and 500–1600 Å (EUV-B). We choose these divisions based on basic technology restrictions since this article is discussing space instrumentation. Normal incidence optics are possible above 50 Å, although with the restriction of using multilayer coatings below 500 Å. The 1600 Å limit is set by the fact that the longest-wavelength, strong transition region line is the C IV line at 1550 Å. The lower limit for soft X-rays is set at 10 keV (1.24 Å) which is the usual definition taken by X-ray astronomers for the division between thermal and non-thermal plasma. A thermal plasma is one with Maxwellian particle distributions and is typically represented by one or two isothermal plasma components, or a continuous differential emission measure distribution. A non-thermal plasma shows enhanced emission above 10 keV beyond what is expected from a thermal electron bremsstrahlung spectrum, and is typically associated with accelerated electrons produced during a flare.
Figure 1. A Skylab S082A overlappogram from 1974 January 26 22:35 UT. Wavelength increases from the left to right. The bright half-Sun image at the left is from O IV λ554.4, and the bright partial image at the right is O V λ629.7. The brightest image to the left of center is from He I λ584.3.

5 OBSERVATION TYPES

The ultimate goal of solar observing at any wavelength is to be able to simultaneously perform 2D imaging and spectroscopy, both at high resolution. That is, each pixel in a 2D image will have a high resolution spectrum with which to apply plasma diagnostics. This has not been realized in the SXR or EUV regions, but is possible in the visible and near-infrared through Fabry-Perot instruments and integral field units.

For spatial resolution, “high resolution” generally means 0.5–2″ in the EUV and SXR ranges. Spectral resolution is defined by the ratio of the wavelength of an emission line to its instrumental width, i.e., \( \lambda / \Delta \lambda \) (for X-rays, wavelength is often substituted for energy and so resolution is given by \( E / \Delta E \)), and values of \( > 500 \) are considered high in the SXR region, \( > 2000 \) in the EUV-A region, and \( > 5000 \) in the EUV-B region.

With simultaneous 2D imaging and spectroscopy not possible, the next-best option has been to image the Sun through a narrow slit and disperse the image in the direction perpendicular to the slit with a grating. This leads to a two-dimensional image on the detector that has wavelength in one direction and spatial information in the other. The first such slit spectrometer in the EUV was HRTS, a rocket experiment flown several times between 1975 and 1992. The first spacecraft slit spectrometers were CDS, SUMER and UVCS on SOHO. No slit spectrometers in the SXR region have yet been flown. The key disadvantage of slit spectrometers is that, to build up two-dimensional images, the slit has to be scanned step-by-step to build up a raster. A solar active region typically has a size around 200″ and so a scan with a 1″ slit with 30 second exposure times would take 100 minutes. Because of this, a slit spectrometer is best used in tandem with a coronal imaging instrument such that the spectrometer observes a relatively small field-of-view and the evolution can be put in context with the active region images.

Without a slit, an imaging spectrometer produces so-called “overlappograms”: each emission line in the spectrum will yield its own image of the Sun which then appear side-by-side in the detector image, spaced by the wavelength separations of the lines. This was most famously done with the S082A instrument on Skylab in the 1970’s (Figure 1). The CDS and EIS instruments were both flown with “slot” options, i.e., slits that were significantly wider than the spectral resolutions of the instruments, thus producing rectangular images at the location of each line. For strong, relatively isolated lines the images are mostly pure and can be used for scientific analysis (e.g., Ugarte-Urra et al., 2009). As shown later in this article, slitless spectrometer designs are being considered for several mission concepts mainly to get around the limited field-of-view problems of slit spectrometers.
Figure 2 illustrates the methods used to focus EUV and SXR radiation. The preferred method is to use normal incidence reflections from the mirror and grating, but this is only possible above 50 Å. Below this wavelength the incoming radiation is simply absorbed by the surface. Between 50 and 500 Å normal incidence optics are only possible by applying multilayer coatings to the surfaces. These are alternating layers of a heavy and light element (Mb and Si are common choices) which lead to strongly enhanced reflectivity over a narrow wavelength range (typically 10–20% of the central wavelength). The first solar telescopes to use multilayer coatings were flown on sounding rockets in the mid-to-late 1980’s (Underwood et al., 1987; Walker et al., 1988) and sub-arcsecond spatial resolution was demonstrated (Golub et al., 1990). Multilayer coatings are ideal for solar imaging as they naturally yield a narrow bandpass that can be tuned to specific emission lines in the EUV spectrum. The first telescope flown on a spacecraft was EIT (Delaboudinière et al., 1995) on SOHO, launched in 1995, followed by TRACE in 1998, EUVI on the STEREO spacecraft in 2006, SWAP on the Proba-2 spacecraft in 2009 (Seaton et al., 2013), AIA on the SDO spacecraft in 2010 (Lemen et al., 2012), and most recently SUVI on the GOES-16 and 17 spacecraft in 2016 and 2018 (Vasudevan et al., 2019). Use of multilayer coatings for spectroscopy was pioneered with the SERTS rocket program (Davila et al., 1993) and the first spacecraft spectrometer to use them was EIS on Hinode (Culhane et al., 2007).

A further advantage of the 50–500 Å region is that EUV photons can be directly detected on specially treated CCDs. The process is to remove (“thin”) some of the back layer of the CCD, and then the incoming radiation illuminates this back side of the detector.

Above 500 Å, broadband optical coatings can be used, giving high and relatively uniform sensitivity over a wide wavelength range, which is particularly valuable for spectroscopy. Examples include SUMER on SOHO and IRIS. The disadvantage of these longer wavelengths is that CCDs have low sensitivity in this region, and so microchannel plates (MCPs) are commonly used to convert incoming photons to electron clouds. These clouds can then be directly detected with an anode detector, such as used for the SUMER and UVCS instruments on SOHO, or they can be converted to visible photons via a phosphor screen which are then detected with a regular CCD (e.g., CDS on SOHO).
Below 50 Å direct imaging requires grazing incidence optics. As illustrated in Figure 2, the incoming radiation is focused off a pair of mirrors that are usually implemented in a cylindrical design (a Wolter-type telescope), with multiple concentric cylinders increasing the effective area. The XRT on Hinode is an example of this design. The disadvantage of grazing incidence is that irregularities on the optical surfaces are magnified, leading to worse imaging performance than normal incidence optics. XRT achieved a 2″ resolution, which compares with 0.3″ for the Hi-C sounding rocket telescope (Kobayashi et al., 2014), which is currently the best performance for a solar EUV multilayer telescope.

Collimators are the least attractive option for imaging, but are often necessary at X-ray wavelengths. At their crudest they achieve spatial resolution simply through restricting the field-of-view. A more sophisticated approach was used by RHESSI (Lin et al., 2002), which had two collimating grids. By rotating the spacecraft continuously every four seconds, a modulation pattern is built up that can be inverted to yield an image of the Sun. A spatial resolution up to 2″ can be achieved this way, but the method has limitations due to low dynamic range and a difficulty of resolving multiple sources. Note that a collimator approach is necessary in the hard X-ray wavelength region, hence grazing incidence optics were not an option for RHESSI.

A step beyond normal incidence optics is the use of Fresnel Zone Plates (FZPs) or Photon Sieves, which could yield spatial resolutions in the 10’s of milliarcsecond range, i.e., two orders of magnitude improvement over the best currently achieved in the EUV. The FZP is an idealized diffractive optic consisting of a circular plate with concentric rings cut into it. The placement of the rings is chosen to enable constructive interference of the transmitted light to yield a focused image. In practice, the rings are replaced with circles of dots or small slits—hence the name “photon sieve”—and they were first discussed in terms of X-ray imaging by Kipp et al. (2001). The key drawback with photon sieves is that the telescope needs a very long focal length of 100 m or more to achieve the highest spatial resolution. This requires a high-precision, formation-flying mission. For example, to yield sharp images, the transverse displacements of the optics spacecraft must be maintained to the size of a detector pixel, which is typically about 10 μm. This technology is becoming available now and is actively pursued by NASA (e.g., Calhoun et al., 2018). In terms of spectroscopy, a photon sieve is of interest because an adjustment of the focal length can lead to a sampling of different parts of an emission line, thus revealing red-shifted or blue-shifted plasma. The first solar mission to employ a photon sieve will be VISORS, a CubeSat project funded by the NSF and led by the University of Illinois at Urbana-Champaign with a launch date in 2023. It will consist of two CubeSats flying in formation. One will host the detector and the other the photon sieve. The He II 304 Å line is targeted and a spacecraft separation of 40 m will yield a spatial resolution of around 0.2″.

6 THE EUV SPECTRUM

Figure 3 shows a synthetic EUV spectrum computed with CHIANTI, with the wavelength ranges of five spectrometers indicated. An “atomic dividing line” in the spectrum is found at about 400 Å, below which most of the emission lines in the spectrum are formed in the corona corresponding to temperatures > 0.8 MK, and above which most lines are formed in the transition region and chromosphere, with temperatures > 20 kK and < 0.7 MK. This dividing line is close to the 500 Å dividing line discussed earlier, below which multilayer coatings are required to enable normal incidence optics. Another important dividing line is 912 Å, which is the Lyman limit corresponding to the hydrogen ionization edge. Although this limit does not impact technology limitations, it does mark a point below which there are no photospheric or low chromosphere lines in the spectrum. These lines are valuable as wavelength fiducial markers due to the small Doppler shifts in these regions.
Young EUV and Soft X-ray Solar Spectroscopy Missions

Figure 3. The blue line shows a synthetic spectrum generated with CHIANTI. The colored boxes denote the wavelength ranges of the five instruments listed at the top of the figure. The “atomic dividing line” is denoted in red and the “technology dividing line” is shown in blue. See the main text for more details on these terms.

Below 400 Å, there are two key groups of iron lines. Between 170 and 212 Å there are the strongest lines from the coronal iron ions Fe\textsc{ix}–\textsc{xiv}, formed at temperatures 0.8–3.0 MK, which have been extensively studied with the \textit{Hinode}/EIS instrument and have also been targets for the EUV multilayer imaging telescopes mentioned in Sect. 5. Between 90 and 140 Å there is group of strong transitions from Fe\textsc{xviii}–\textsc{xxiii}, formed between 7 and 14 MK that offer excellent diagnostics of active regions and flares but have never been studied with a spacecraft spectrometer.

Above 400 Å the dominant transitions are the Lyman-\(\alpha\) lines of hydrogen and ionized helium at 1216 and 304 Å, and the 584 Å line of neutral helium. The most abundant elements of the lithium, beryllium, sodium and magnesium isoelectronic sequences all give rise to strong lines, which continue down below 400 Å (Table 2).

Table 2. Wavelengths (in Å) of strong lines in the EUV.

| Element | Li-like | Be-like | Na-like | Mg-like |
|---------|---------|---------|---------|---------|
| C       | 1548.2, 1550.7 | 977.0 | –       | –       |
| N       | 1238.8, 1242.8 | 765.2 | –       | –       |
| O       | 1031.9, 1037.6 | 629.7 | –       | –       |
| Ne      | 770.4, 780.4 | 465.7 | –       | –       |
| Mg      | 609.8, 624.9 | 368.1 | –       | –       |
| Si      | 499.4, 520.7 | 303.3 | 1393.8, 1402.8 | 1206.5 |
| Fe      | 192.0, 255.1 | 132.9 | 335.4, 360.8 | 284.2 |

Although the > 400 Å region mostly contains cool emission lines, there are an important set of coronal lines that are due to so-called “forbidden” transitions. That is, transitions that occur within the ground atomic configurations of the ions that have small but non-zero transition rates. Crucially these transitions
enable spectrometers operating in the $>400$ Å region to have some coronal capability and this has been exploited by the SPICE and IRIS spectrometers discussed in the next section.

## 7 EUV INSTRUMENTATION

There are several EUV instruments currently operating, including imagers on STEREO, SDO and the GOES-16 and 17 spacecraft. In terms of spectroscopy, the key instruments are EIS, IRIS and SPICE which are all imaging slit spectrometers. EIS (Culhane et al., 2007) has been operating on the Japanese Hinode mission for over 14 years. It obtains high resolution spectra in two bands at 170–212 and 246–292 Å, with a spatial resolution of 3–4′′. Spectral resolution ($\lambda/\Delta \lambda$, where $\Delta \lambda$ is the instrumental width of the emission lines) is 3000–4000, and the wavelength bands mostly include lines formed in the temperature range 0.5–20 MK. Our definition of EUV for this article includes wavelengths below 1600 Å and so IRIS (De Pontieu et al., 2014), with its two channels at 1332–1358 and 1389–1407 Å, falls within our remit and was launched in 2013. Spatial resolution is 0.3–0.4′′, the best of any of the spacecraft instruments observing the Sun, and spectral resolution is around 50 000. The narrow wavelength bands give access to mostly chromospheric and transition region lines, with the exceptions of coronal forbidden lines of Fe XII and Fe XXI (formed at 1.5 and 11 MK, respectively), although the former is weak and rarely observed. IRIS also has a slitjaw imager, enabling the slit to be placed within simultaneous high-cadence chromospheric and/or transition region images.

SPICE (Spice Consortium et al., 2020) was launched on the Solar Orbiter spacecraft in 2020 February and the optical design is similar to EIS but with two longer wavelength bands at 704–790 and 972–1050 Å. The spatial and spectral resolutions are 4′′ and 1500–2000, respectively. Note that, since Solar Orbiter will reach distances of 0.3 AU from the Sun, then the effective spatial resolution will be up to a factor three better compared to a spectrometer at 1 AU. The wavelength bands give more complete temperature coverage than EIS and IRIS, particularly through the chromosphere and transition region, but the lines formed in the coronal range 1–4 MK are significantly weaker than those observed by EIS.

The sections below discuss new mission concepts in the EUV wavelength range, divided between slit and slitless spectrometers.

### 7.1 Slit spectrometers

#### 7.1.1 Solar-C_EUVST

Solar-A and Solar-B are Japanese missions that were renamed Yohkoh and Hinode on launch. The concept for the successor Solar-C mission has evolved over time, but Japan and the USA have both recently approved the Solar-C_EUVST concept, which is scheduled for launch in 2026. Based on the LEMUR concept (Teriaca et al., 2012) that was a component of a larger, multi-instrument configuration of Solar-C, EUVST is an imaging slit spectrometer with a slitjaw imager (the latter similar to that flown on IRIS, De Pontieu et al., 2014). The design is something of a hybrid of EIS and SPICE. The primary mirror and grating combine multilayer coatings and a broadband boron carbide coating to yield high efficiency in the longer UV wavebands of 690–850, 925–1085 and 1115–1275 Å, together with the EUV waveband of 170–215 Å. This is critical to giving EUVST the most complete temperature coverage of any solar spectrometer, with strong emission lines formed throughout the chromosphere, transition region, corona and flaring corona. The spatial resolution of 0.4′′ is also comparable to IRIS, and EUVST will be the first spacecraft to achieve this resolution for wavelengths below 1000 Å.

#### 7.1.2 EUNIS

EUNIS is a successor to the series of SERTS rocket experiments flown in the 1980’s and 90’s by a team at NASA Goddard Space Flight Center. It contains two independent imaging slit spectrometers with spatial...
resolutions of 3–4′′ and spectral resolutions of about 2000, and it has been flown in 2006, 2007 and 2013. The fourth flight has been delayed because of the COVID-19 pandemic but should take place in 2021. A new grating and multilayer coating will be used to obtain the first high resolution solar spectra in the wavelength region 90–110 Å for several decades. In addition to observing the strong Fe XVIII and Fe XIX emission lines in this region (solar activity permitting), the spectra will also be used to characterize cooler lines that contribute to the 94 Å imaging channel of AIA.

7.1.3 MUSE

MUSE is, at the time of writing, one of five mission concepts under review by NASA for selection as a MIDEX, with a launch date in the 2025–26 timeframe. It is a slit spectrometer, but with the novelty of having 37 closely-separated, parallel slits. Each slit produces its own two-dimensional spectral image on the detector, but offset from each other. Thus the spectral and spatial dimensions are mixed in the detector-X direction. The image separations are 0.39 Å, corresponding to 4.5′′. Ordinarily the mixing of the spectral images would make the data difficult to analyze, but the narrow bandwidths of multilayer coatings are used to advantage to minimize the overlapping of the spectral images. By choosing relatively isolated lines in the spectrum at 108 (Fe XIX), 171 (Fe IX) and 284 Å (Fe XV) it can be shown that plasma properties such as line-of-sight velocity, temperature and line broadening can be accurately extracted (Cheung et al., 2019). The lines are formed at temperatures 10, 0.8 and 2.5 MK, respectively. Spatial resolution will be 0.4′′, comparable to the best yet obtained for an EUV instrument (the Hi-C rocket experiment), and spectral resolution will be 2500 to 5000, depending on the channel.

The great achievement of MUSE would be to effectively meet the goal of simultaneous two-dimensional imaging and high-resolution spectroscopy. Thus complex, highly dynamic features could be monitored on timescales of seconds without the highly-restricted view of a single-slit spectrometer. The downside is that the temperature coverage is not as complete as a single-slit spectrometer due to the limited number of channels. However, this is partly compensated for by an EUV multilayer context imager with two channels at 304 and 195 Å, the former giving images of the upper chromosphere and the latter images at 1.5 MK, midway between the Fe IX and Fe XV lines.

7.1.4 VERIS

VERIS is a sounding rocket experiment led by the Naval Research Laboratory that has been funded for a second launch following the first in 2013. It is an imaging slit spectrometer covering the region 940–1140 Å. The spectral range is comparable to the long-wavelength channel of SPICE, with a number of strong chromosphere, transition region and coronal emission lines. The spectral and spatial resolutions will be significantly better at around 5000 and 0.4′′, respectively.

7.2 Slitless spectrometers

7.2.1 COSIE

COSIE is a novel EUV instrument concept from the Smithsonian Astrophysical Observatory that enables both wide-field EUV imaging of the solar disk and outer corona (to distances of 3 $R_\odot$), and slitless spectroscopy of the entire solar disk. A mechanism between the entrance aperture and the focus mirror has a flat mirror for the imaging mode, which can flip over to a grating for the spectroscopy mode. Both the mirror and grating have multilayer coatings that target the 186 to 205 Å range. COSIE is not currently selected for any flight opportunities, but the concept along with the science justification is described in detail by Golub et al. (2020). Due to the slitless design, the spectral data would require deconvolution techniques to extract physical parameters from the images and this has been explored by Winebarger et al. (2019) using the method developed for MUSE (Sect. 7.1.3).
7.2.2 SunCET

SunCET (Mason et al., 2021) is a CubeSat concept that is currently under Phase A review with NASA. It has some similarities with COSIE in that it would have a compact EUV imager covering both the solar disk and the extended corona, with the aim of tracking coronal mass ejections. A wide-band multilayer coating will be used to cover the 170–200 Å region. In terms of spectroscopy, there will be an EUV solar disk-averaged spectrometer operating from 170 to 340 Å with modest 1 Å resolution. The design is based on one of the EUV spectrograph channels of the EVE instrument on SDO (Woods et al., 2012).

7.2.3 FURST

The FURST rocket experiment, led by Montana State University, is scheduled for launch in 2022 and is unique amongst the EUV experiments considered here in covering a very broad wavelength range (1200–1800 Å) with a high spectral resolution of 10,000. Such a wide spectral range is usually prohibited by the limited size and/or number of CCD cameras for space instruments or, for EUV-A range instruments, the small bandpass of multilayer coatings. The optical design is also distinct with the reflecting surfaces being seven cylinders arranged along the Rowland circle (see Kohl et al., 1995, for a description of a Rowland circle design applied to the UVCS instrument on SOHO). The cylindrical reflections result in the solar images being compressed to narrow slits in the direction parallel to the dispersion direction, thus giving narrow emission lines in the final spectrum despite the full-disk image information they contain. The mission goal is to obtain a Sun-as-a-star spectrum that can be compared with those obtained of other stars with the Hubble Space Telescope.

7.2.4 Hi-C/COOL-AID and ESIS

Hi-C is a sounding rocket EUV imaging instrument that was flown in 2012 (Cirtain et al., 2013) and 2018 (Rachmeler et al., 2019), achieving the best spatial resolution of the corona yet obtained with a multilayer-based imaging telescope. (Note that IRIS has achieved a similar resolution when observing the long-wavelength Fe XXI 1354.1 Å emission line but does not use multilayer coatings.) The third flight is currently planned in 2024 as part of a special flare campaign whereby Hi-C and FOXSI (Sect. 9.4) will be launched together while a flare occurs on the Sun. Hi-C will obtain images in a channel centered on the Fe XXI 128.8 Å line (formed at 11 MK). A new addition to Hi-C will be COOL-AID1, a pair of identical slitless EUV spectrometers.

COOL-AID also targets the Fe XXI 128.8 Å line and the optical design is based on COSIE. Flares at this temperature are typically compact and Doppler shifts will lead to a smearing of the image in the solar-east direction, if blueshifts, and to solar-west if redshifts. The second of the COOL-AID spectrometers is identical to the first, but the grating dispersion is in the orthogonal direction. Doppler shifts will thus lead to smearing in the north-south directions, rather than east-west. By combining the two images it will thus be possible to distinguish spatial structure from velocity structure.

This observation technique is a basic form of Computed Tomography Imaging Spectroscopy, which was recently investigated on the Sun with the ESIS sounding rocket experiment. Launched in 2019 and led by Montana State University, ESIS is a slitless spectrometer that feeds the solar image to four gratings, with dispersion directions that are progressively stepped by 45 degrees from each other. The wavelength band includes He I λ584.3 and O V λ629.7 (see Fig. 1). As with COOL-AID, Doppler shifts will result in smearing of compact bright points in the gratings’ dispersion directions. Thus a small “explosion” may result in smears in all of the gratings’ images, but a collimated jet may only lead to smearing in one or two

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1 Hi-C and Kool-Aid are rival brands of fruit-flavored drinks in the US.
The blue line shows a synthetic flare spectrum generated with CHIANTI. The green line shows the same spectrum, but with only lines from H and He-like species. Boxes show the wavelength coverage of MaGIXS, bent crystal spectrometers (BCS), and Si-PIN/SDD detector spectrometers. Boxes show the wavelength coverage of MaGIXS, bent crystal spectrometers (BCS), and Si-PIN/SDD detector spectrometers. Boxes show the wavelength coverage of MaGIXS, bent crystal spectrometers (BCS), and Si-PIN/SDD detector spectrometers. Boxes show the wavelength coverage of MaGIXS, bent crystal spectrometers (BCS), and Si-PIN/SDD detector spectrometers. Boxes show the wavelength coverage of MaGIXS, bent crystal spectrometers (BCS), and Si-PIN/SDD detector spectrometers. Boxes show the wavelength coverage of MaGIXS, bent crystal spectrometers (BCS), and Si-PIN/SDD detector spectrometers.

Figure 4. The blue line shows a synthetic flare spectrum generated with CHIANTI. The green line shows the same spectrum, but with only lines from H and He-like species. Boxes show the wavelength coverage of MaGIXS, bent crystal spectrometers (BCS), and Si-PIN/SDD detector spectrometers. Boxes show the wavelength coverage of MaGIXS, bent crystal spectrometers (BCS), and Si-PIN/SDD detector spectrometers. Boxes show the wavelength coverage of MaGIXS, bent crystal spectrometers (BCS), and Si-PIN/SDD detector spectrometers. Boxes show the wavelength coverage of MaGIXS, bent crystal spectrometers (BCS), and Si-PIN/SDD detector spectrometers. Boxes show the wavelength coverage of MaGIXS, bent crystal spectrometers (BCS), and Si-PIN/SDD detector spectrometers. Boxes show the wavelength coverage of MaGIXS, bent crystal spectrometers (BCS), and Si-PIN/SDD detector spectrometers.

of the gratings’ images. The ESIS data are currently being analyzed, but numerous dynamic events have been detected (A. Winebarger, private communication).

8 THE SOFT X-RAY SPECTRUM

At first glance the SXR spectrum seems less attractive for studying the solar atmosphere as there are no strong transition region lines apart from the C V and N VI lines at 40.7 and 29.1 Å and, as discussed in Sect. 5, there are difficulties in performing high resolution imaging spectroscopy. The coronal SXR lines are largely formed at temperatures of 5 MK or higher and so science objectives are usually focused on flares and active region heating. This has the consequence that any missions featuring SXR capability should ideally be flown prior to or during solar maximum. (The next maxima are expected to take place in the few years around 2025 and 2036.)

Figure 4 shows a soft X-ray spectrum generated with CHIANTI over the region 1–50 Å (0.1–12 keV). The three key features are (i) sets of H-like and He-like ions from carbon through nickel; (ii) lines from Fe XVII–XXIV in the 11–17 Å region; (iii) continuum emission that increases with energy.

The H and He-like ions of iron, Fe XXV and Fe XXVI, are of particular interest as they give rise to strong transitions at temperatures inaccessible to EUV wavelengths (Fe XXIV is the hottest iron ion in the EUV, with a strong line at 192 Å). Both species have been previously studied at high resolution with Bragg Crystal Spectrometers on board SMM and Yohkoh.

Due to the wide range of elements available, H and He-like ions also offer excellent FIP bias diagnostics, and examples include Sylwester et al. (2008) and Phillips et al. (2018). These diagnostics have even been applied to low-resolution spectra (Caspi et al., 2015).

The Fe XVII–XXIV lines arise from transitions between \( n = 2 \) and \( n = 3 \) shells. (Weaker transitions between \( n = 2 \) levels are found in the EUV between 90 and 140 Å.) A large number of transitions are found between 11 and 17 Å so high spectral resolution is required to resolve them sufficiently to apply the
many temperature and density diagnostics that these ions offer. Combining these iron ions with the H-like ion Ne X gives an excellent FIP bias diagnostic (e.g., Brinkman et al., 2001).

The continuum in the SXR region comes predominantly from free-free (bremsstrahlung) and free-bound emission and is dominated by hydrogen, thus emission line to continuum comparisons can yield “absolute” element abundances, i.e., relative to hydrogen.

9 SOFT X-RAY INSTRUMENTATION

The only currently operating solar mission with SXR spectroscopic capability is STIX on Solar Orbiter, which was launched in 2020. It uses collimating grids (see Sect. 5) to enable a spatial resolution down to 7″ and, although mainly focused on hard X-rays, the instrument has coverage down to 4 keV but with a resolution of only 1 keV. There are also disk-averaged solar spectrometers flown on planetary missions as discussed in Sect. 9.1.

RHESSI, although principally a hard X-ray mission, had some SXR capability but ceased operations in 2018 after 16 years in orbit. The first MinXSS CubeSat was deployed from the ISS in 2016 and operated for one year, as planned. The follow-on MinXSS-2 was intended to have a five-year lifetime after launch in 2018, but it failed within the first month. The DAXSS on INSPIRESat-1 (see below) is considered the successor.

9.1 Silicon PIN and Drift detectors

Compact X-ray detectors from the company AMPTEK have proven very successful for obtaining moderate resolution soft X-ray spectra from a package with dimensions approximately 15 mm. A detector was first flown on NASA’s NEAR asteroid mission in 1996 in order to measure the solar X-ray flux. This measurement is often important for planetary science missions as solar X-rays illuminate the body’s surface and the resulting fluorescent X-ray spectrum leads to valuable composition data. Detectors were also flown on SMART-1, Chandrayaan-1 (both lunar missions) and the Mercury MESSENGER mission. The solar data have proven valuable for solar flare studies (e.g. Dennis et al., 2015). The most recent planetary spacecraft with a solar X-ray spectrometer is the Indian Chandrayaan-2 mission (Mithun et al., 2020), which was launched in 2019.

The AMPTEK detectors are either silicon PIN (Si-PIN) or silicon drift detectors (SDD) and they both come in an all-in-one configuration referred to as X-123. SDDs are more expensive but allow higher count rates and slightly better spectral resolution. Spectral coverage is typically 1–20 keV and resolution is about $E/\Delta E = 30$ to 50, which is sufficient to resolve spectral features from which element abundances can be derived (Dennis et al., 2015; Moore et al., 2018).

The SphinX instrument (Gburek et al., 2013) on board the Russian CORONAS-Photon mission used an earlier version of the AMPTEK detector, while the X-123 was flown on the MinXSS-1 and 2 Cubesats (Moore et al., 2018) in 2016 and 2018, although the latter failed before data could be obtained.

INSPIRESat is a series of satellites developed by a consortium of space universities led by the University of Colorado at Boulder. The first will be launched in 2021 and include the Dual-zone Aperture X-ray Solar Spectrometer (DAXSS), which was first flown on a sounding rocket (Schwab et al., 2020). The key advance over the MinXSS instruments upon which it is based is an increase in the size of the primary aperture to increase sensitivity to high-energy photons, and the insertion of a Kaplon filter behind the primary to attenuate the more intense flux of low-energy photons. The result is a more balanced distribution of low and high-energy photons.
We note that CCD and CMOS detectors also offer energy resolution in the SXR region, as the detectors are able to measure the numbers of electron-hole pairs created by the incoming photons. (The Lyman-α line of Fe \textsubscript{XXVI} produces almost 2000 pairs, for example.) The spectral resolution is limited to about 100 eV, thus the performance is not as good as the Si-PIN or SDD detectors. Combining a CCD or CMOS with a focusing telescope, however, does then enable imaging spectroscopy. Note that a CMOS sensor has higher noise than a CCD but wider dynamic range and the ability to read out individual pixels separately. Sections \textsection{9.7.1} \textsection{9.4} and \textsection{9.7.2} discuss instruments that use CMOS sensors.

9.2 Crystal spectrometers

Certain crystals can reflect X-rays at a specific wavelength, determined by the angle of incidence, as first determined by L. and W.H. Bragg in 1913. If the crystal is rotated to modify the incidence angle, then a spectrum can be built up. A single crystal will give access to a range $\approx \pm 40\%$ of the central wavelength. The Flat Crystal Spectrometer on SMM featured seven different crystals on a rotating drum structure, enabling almost complete wavelength coverage from 1.4 to 22.5 Å. The DIOGENESS instrument \cite{Sylwester2015} on the Russian CORONAS-Photon mission also featured a rotating drum design, but was only operational for a few weeks in 2001. The next iteration of this type of instrument will be part of the SOLPEX instrument package \cite{Steslicki2014,Sylwester2019} to be flown with the Russian KORTES experiment to the ISS in the 2021–2022 time-frame. The Rotating Drum X-ray Spectrometer (RDS) will have seven crystals placed on a drum that rotates ten times per second to achieve high time resolution data of flares. The spectra will cover 0.4–23 Å and be captured on SDDs.

Bent crystal spectrometers (BCS) take advantage of Bragg diffraction to yield high resolution spectra over a narrow wavelength region without the need for scanning. They have been flown on SMM \cite{Culhane1981}, \textit{Yohkoh} \cite{Culhane1991} and CORONAS-Photon \cite{Sylwester2005} but there are currently no plans to fly a new instrument.

9.3 MaGIXS

Imaging slit spectrometers have been very successful at EUV wavelengths, but none have been flown in the SXR range. This will change with the launch of the sounding rocket experiment MaGIXS \cite{Kobayashi2018} in 2021. It will observe the 6–24 Å region without the need for scanning and have spatial resolution along the slit of 5\arcsec. The spectral resolution of 500 is not as good as that possible with the crystal spectrometers, but significantly better than for the silicon detector instruments.

Simultaneous coverage of the Fe \textsubscript{XVII}--\textsubscript{XXIII} lines with the H and He-like lines of oxygen through silicon will lead to excellent plasma diagnostics in the 3–10 MK temperature range. This is important for understanding the heating of solar active regions. The spectra would also be excellent for flare measurements, but this is unlikely for a 5-minute rocket flight.

9.4 FOXSI

FOXSI is a sounding rocket experiment that was flown in 2012, 2014 and 2018. It was the first solar instrument to obtain solar images at hard X-ray wavelengths using focusing optics \cite{Krucker2014}, and the detectors yield modest spectral resolution. Wavelength coverage extends to the 4–10 keV SXR region, where spectral resolution was around 10–20. The data have been valuable for studying active region heating \cite{Ishikawa2017,Athiray2020}.

The FOXSI concept was proposed for the 2016 SMEX call, but was not selected after reaching Phase A. For the 2019 MIDEX call it was teamed with an EUV imager and the concept was named FIERCE, but it was not selected for Phase A. A key difference with the rocket experiments is that the spacecraft versions
would have had extendable booms, extending the spectral coverage from around 20 keV up to around 70 keV.

The next FOXSI flight is planned for 2024 as part of a special flare campaign coordinated with another launch of the Hi-C EUV imager. The latter will include the COOL-AID EUV spectrometer (Sect. 7.2.4).

9.5 CubIXSS
CubIXSS is a CubeSat mission concept that is currently under Phase A review with NASA. It consists of two distinct instruments: a spatially-integrated SXR spectrometer, the Small Assembly for Solar Spectroscopy (SASS), that is an evolution of the MinXSS spectrometers, and the Multi-Order X-ray Spectral Imager (MOXSI). The latter has a set of five pinhole cameras, four of which yield full-disk images of the Sun in X-ray lines. The fifth camera feeds a transmission grating to yield full-disk, overlappogram spectra (see Fig. 1). Some more details are available in the White Paper of Caspi et al. (2017).

9.6 Microcalorimeters
Microcalorimeter detectors enable simultaneous 2D imaging and high-resolution spectroscopy at SXR wavelengths, and thus are a high priority for all areas of X-ray astronomy. The Japanese astrophysics spacecraft Hitomi was the first to fly a microcalorimeter as part of the Soft X-ray Spectrometer (SXS). Sadly Hitomi perished after obtaining only a single observation of the Perseus galaxy cluster (Hitomi Collaboration et al., 2016). The SXS had a $6 \times 6$ 2D pixel array with energy resolution of 7 eV between 0.3 and 12 keV (Takahashi et al., 2018), which is comparable to the crystal spectrometers.

The high count rates from the Sun pose a problem for microcalorimeters compared to other astrophysical sources, and development progress lags behind that in Astrophysics. Some discussion of the scientific possibilities of microcalorimeters is given in the White Paper of Laming et al. (2010), while technical aspects are covered in Bandler et al. (2010) and Bandler et al. (2013).

9.7 Mission concepts
9.7.1 PhoENIX
Physics of Energetic and Non-thermal Plasmas in the X-region (PhoENIX) is a Japanese mission concept currently considered for the solar maximum in the mid-2030’s. It consists of three separate instruments: Soft X-ray Imaging Spectrometer (SXIS), Hard X-ray Imaging Spectrometer (HXIS) and Soft Gamma-Ray SpectroPolarimeter (SGSP).

SXIS would combine a Wolter-type telescope with spatial resolution around 1\" with a photon-counting CMOS sensor. The latter yields high time resolution and modest spectral resolution (comparable to the silicon drift detectors), and was first flown on the FOXSI-3 sounding rocket in 2018 (Narukage 2019).

9.7.2 SSAXI
SSAXI is a SmallSat concept proposed by the Smithsonian Astrophysical Observatory (Hong et al. 2019) that would perform imaging spectroscopy in the 0.6–6 keV range with spatial and spectral resolutions of 30\" and 10, respectively. There are six small Wolter-type telescopes feeding CMOS sensors with energy-resolving capability (similar to that used on the FOXSI-3 flight). Unlike other X-ray missions, SSAXI would be focused on small-scale flaring activity in the quiet Sun and active regions and so would be preferentially launched during solar minimum.

10 SUMMARY
This article has attempted to identify the new technologies and missions that will operate at soft X-ray and extreme ultraviolet wavelengths in the years to come. These wavelength ranges are critical for understanding energy and mass flow through the solar atmosphere and how million-degree plasma is heated.
Table 3. Summary of future missions.

| Mission   | On the way | Proposed | Long term |
|-----------|------------|----------|-----------|
| EUV       | EUNIS      | MUSE     | COSIE     |
| EUVST     |            | SunCET   |           |
| FURST     |            |          |           |
| VERIS     |            |          |           |
| COOL-AID  |            |          |           |
| SXR       | MaGIXS     | CubIXSS  | PhoENIX   |
|           | INSPIRESat-1/DAXSS | SOLPEX | SSAXI     |
|           |            | Microcalorimeters |           |
| FOXSI     |            |          |           |

and maintained. The missions are listed in Table 3 and classified according to whether they are on the way, are proposed, or whether they are just concepts at this point.

I note that there are currently no large, “billion-dollar-class” solar missions planned for the future and so opportunities for the traditional large, high-resolution instruments flown in the past are limited to smaller Explorer-class missions and missions-of-opportunity. However, as hopefully demonstrated in this article, there are many innovative, low-cost CubeSat and SmallSat concepts that should yield exciting new results in the future.

CONFLICT OF INTEREST STATEMENT
The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

AUTHOR CONTRIBUTIONS
All text and figures were created by the author.

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