

SIRIUS: Stellar and ISM research via in-orbit ultraviolet spectroscopy

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ABSTRACT

SIRIUS is a low cost, observatory-class mission developed from the J-PEX sounding rocket program. It is a mature concept and has undergone a UKSA-funded study before being proposed for the ESA mini-F mission call. It was moved to the F3 program and approved for a stage 2 submission, now under evaluation. The key science goals of SIRIUS are to understand the environments in the nearby regions of the Galaxy, including study of the influence of stellar activity on exoplanet habitability, study of white dwarf atmosphere to measure composition of exoplanetary remnants and observation of the wider interstellar environment in which planetary systems exist. The instrument is a normal incidence objective grating spectrometer operating the EUV from 17 to 26 nm, with a resolving power of 5000. The main goal of the SIRIUS mission is to understand this cosmic feedback system within the Local Cavity and how it influences the habitability of our region of the Galaxy.

Keywords: EUV spectroscopy, Multilayer gratings, MCP detectors, Low-cost space missions

1. INTRODUCTION

SIRIUS is a mission designed to carry out extreme ultraviolet spectroscopy of stars and the local interstellar medium. It was proposed for the ESA F2 call and was selected as the back-up mission, validating its technical readiness and scientific quality. Subsequently, SIRIUS was funded by the United Kingdom Space Agency science bi-lateral program for a 1-year phase 0 study aimed at reducing mission costs, using an off-the-shelf approach to spacecraft procurement coupled with techniques to reduce the satellite launch envelope, allowing a rideshare launch, compatible with small European launchers. A detailed costing and schedule analysis demonstrated that the SIRIUS mission can be delivered within a £50M envelope, allowing world-class observatory level science to be delivered at modest cost. SIRIUS was proposed for the recent ESA mini-F exploratory call but was moved into the F3 competition, where it is currently undergoing evaluation. In this paper, we describe the science goals of the mission, the science requirements and the instrument design. We summarize the results of the UKSA-funded study and its imaginative technical approach to reducing mission cost.

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2. SCIENTIFIC GOALS OF SIRIUS

Background

The formation and evolution of stars, their interaction with interstellar material and the ultimate effect of all the various physical processes on their planetary systems are still poorly understood. Crucial elements of the picture concern the levels of activity in main sequence stars and the resulting stellar winds, eruptions, and EUV irradiances, all of which can directly affect planetary environments on a range of timescales. In addition, stellar winds control the flow of material and flux of cosmic rays from the galactic environment, which also have a potential influence on the climate of any nearby extrasolar planets. Ultimately, stars recycle material back into the ISM enhancing galactic metal content, through supernovae and possibly novae plus mass-loss during the production of white dwarfs. All the important processes involved in these stellar lifecycles are traced by the presence of hot (10^5 - 10^7 K) gas which is best observed in the EUV. SIRIUS will investigate the density, temperature, composition, structure, and dynamics of hot astrophysical plasmas in the 10^5 to 10^7 K range, addressing basic questions of stellar evolution and galactic structure.

The Sun and several nearby stars are embedded in a complex of warm (~ 7000 K) and partially ionized interstellar clouds [1][2]. In turn, this cloud complex resides in an unusually low neutral gas density part of our Galaxy, a ~ 100 pc diameter rarefied cavity often termed the 'Local Cavity' [3] that appears to have been created by supernovae 14 Myr ago [4][5][6]. This region is filled with a diverse population of stars, and its structure has been influenced by their lifecycles, which have, conversely, been affected by the environment in which they exist. SIRIUS is a high-resolution Extreme Ultraviolet (EUV) spectroscopy mission, with a wavelength range 170 - 260 Å and spectral resolving power of 5000, able to perform observations of nearby stars and the interstellar medium (ISM). The main goal of the SIRIUS mission is to understand this cosmic feedback system within the Local Cavity and how it influences the habitability of our region of the Galaxy.

Key Science Objectives

The key scientific objectives of the mission are to:

Examine the structure and dynamics of stellar coronae and their influence on exoplanet atmospheres: to determine the evolution of coronal activity over a wide range of star classes/ages and measure the influence of this activity on exoplanet atmospheres, astrospheres and the ISM.

Probe the structure & ionization of the Local Interstellar Gas: measuring density, temperature, ionization state, and depletion level of gas clouds along many lines-of-sight within 200 pc of the Sun.

Study the evolution of white dwarfs: to examine the physical mechanisms controlling the atmospheric abundances and understand how important elements such as CNO are returned to enrich the interstellar medium; determine the incidence of circumstellar material associated with the disruption of remnant planetary systems.

3. THE EUV SPECTROGRAPH

The SIRIUS spectrograph design is based on a sounding rocket payload, J-PEX, which was flown successfully from the White Sands Missile Range in New Mexico on two occasions [7][8]. The spectrum of the hot white dwarf G191-B2B, reported by Cruddace et al. [7] is shown in Figure 1. The J-PEX design utilised four blazed ion-etched multilayer-coated diffraction gratings to yield high reflectivity. While these multilayers achieve high efficiency, this is over a limited waveband. Therefore, to cover the wider 170-260 Å spectral range required for SIRIUS, we deploy two pairs of gratings, each pair having a different waveband, focused onto a single detector. Figure 2 shows the slitless design comprising a figured diffraction grating operating at near-normal incidence in a Wadsworth mount [9]. This basic design is simple, has small aberrations, and yields large collecting areas. The spectrometer has a door, which makes a dust-and light-tight aperture seal. Light enters through a collimated aperture, which minimizes the flux of diffuse background radiation, and is diffracted by a grating to form a focused spectrum of a chosen order onto an MCP detector [10].

The SIRIUS spectrograph has a focal length of 2-m and each grating a geometric area of 143 cm² (total 572 cm²). Figure 3 and Table 1 show SIRIUS' predicted effective area. The thick black line in Figure 3 is the summed effective area in regions where the two wavebands overlap. The effective area is the product of geometrical area, grating groove efficiency, multilayer reflectance, collimator transmission, filter transmittance, and detector quantum efficiency (QE) (see Table 1).

We have assumed conservative values for these based on actual performance data. SIRIUS will achieve peak effective areas of at least 10-12 cm² with coverage exceeding 5 cm² over ~60% of the range 170-260 Å. An important point is that the effective area of SIRIUS is about an order of magnitude greater than the EUVE spectrometer, which operated at < 1/10 the resolving power of our instrument. SIRIUS also has a collecting area several times that of the LETG on the flagship Chandra X-ray observatory.

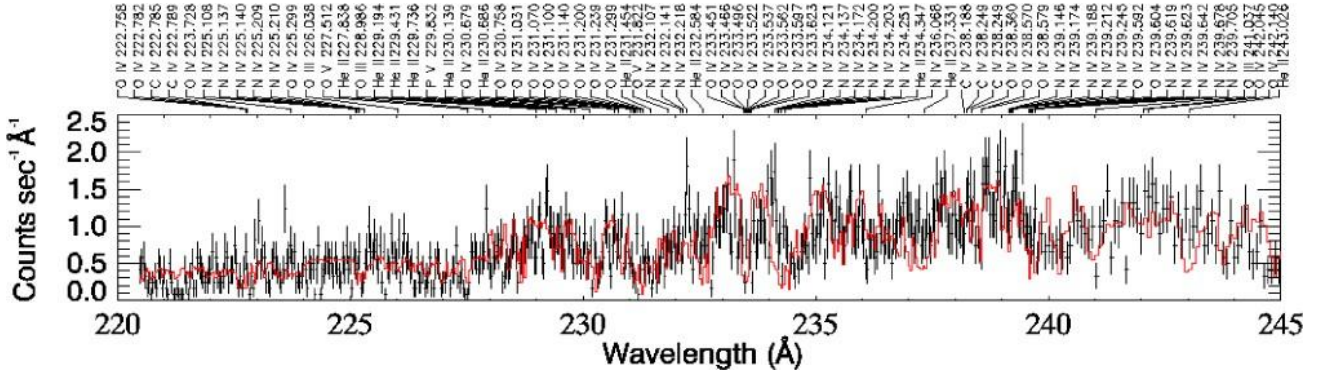


Figure 1. High-resolution spectrum of the white dwarf G191-B2B (black error bars), obtained in a 300s J-PEX observation. The best-fit spectrum (red histogram) yields a photospheric He abundance of 1×10^{-6} and LISM He II column density of $5.9 \times 10^{17} \text{ cm}^{-2}$. The most prominent absorption lines are identified in the top panel.

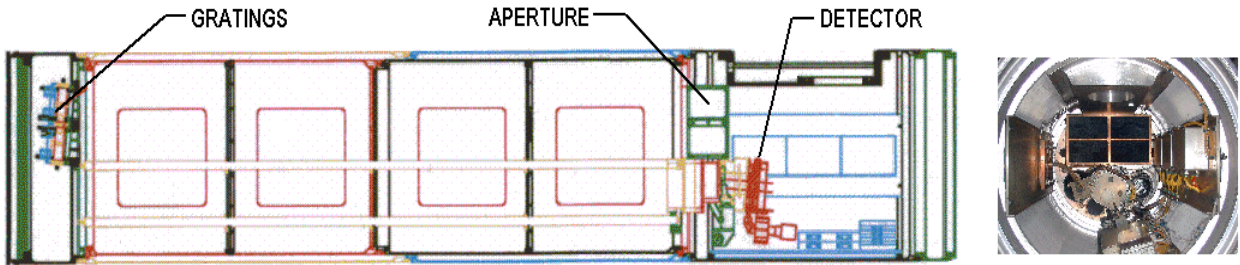


Figure 2. (Left) Optical layout of the SIRIUS spectrometer, based on the J-PEX design showing the off-axis arrangement of the MCP and the grating pairs on separate mounts. (Right) Photograph of the aperture of the actual J-PEX spectrograph showing the collimators (black rectangles), below these is the MCP detector and to the immediate left the associated electronics boxes. The two circular apertures are optical tracking telescopes.

4. A TECHNICAL APPROACH TO COST REDUCTION

Spectrograph optical bench

High-resolution observations are inherently difficult to implement in space instruments. However, a slitless spectrometer such as SIRIUS has an advantage over competing designs (e.g. Rowland circle with slit) in that it does not place tight requirements on the S/C attitude control system (AOCS). Modest pointing error (APE/AKE, 1 arcmin), drift, and jitter (RPE, 1 arcsec/sec combined) may be tolerated provided these motions are calibrated out. Ray tracing results predict a

depth of focus of $\pm 100 \mu\text{m}$ for the SIRIUS gratings. Piezoelectric actuators are used to focus each grating during ground calibration and observations of WD stars are used on orbit to monitor focus. Internal flexure caused by thermal, gravity gradient, or other sources might also degrade alignment and wavelength calibration, thus reducing spectral resolution. Alignment can be monitored on time scales short compared to target integration times to calibrate (in data processing) S/C jitter and instrument flexure with a non-dispersive region of the grating to focus a target image on the MCP detector. This will (i) determine any bore-sight shift suffered by the AOCS star tracker through launch loads, (ii) serve as redundant backup to star tracker monitoring of AOCS motions, and (iii) monitor flexure between the grating and MCP. This system was successfully employed on J-PEX to acquire precise (RKE, 1 arcsec) time-resolved pointing knowledge. This information was de-convolved from the time-tagged photon positions in the raw detector images to recover the design spectral resolution and is the approach planned for SIRIUS.

The spectrograph structure and the 2-m focal length of the instrument place significant demands on the overall spacecraft volume for launch, but it is mostly empty space between the two decks that house the gratings and the focal plane. Reduction of the dimensions of the complete satellite at launch can provide an opportunity for a shared launch, yielding a reduction in launch costs. The UK Space Agency science bi-lateral program supported a 1-year phase 0 study of SIRIUS aimed at reducing mission costs, using an off-the-shelf approach to spacecraft procurement coupled with techniques to reduce the satellite launch envelope, allowing a shared launch. During the UKSA study, we worked with Oxford Space Systems, specialists in in-orbit deployment mechanisms, to evaluate a post-launch deployment system for SIRIUS. From several options considered, the optimum solution is an expandable barrel design (figure 4). The stowed payload is less than 1/3 the deployed length. When deployed, the system meets the alignment and focusing requirements of the spectrograph discussed above.

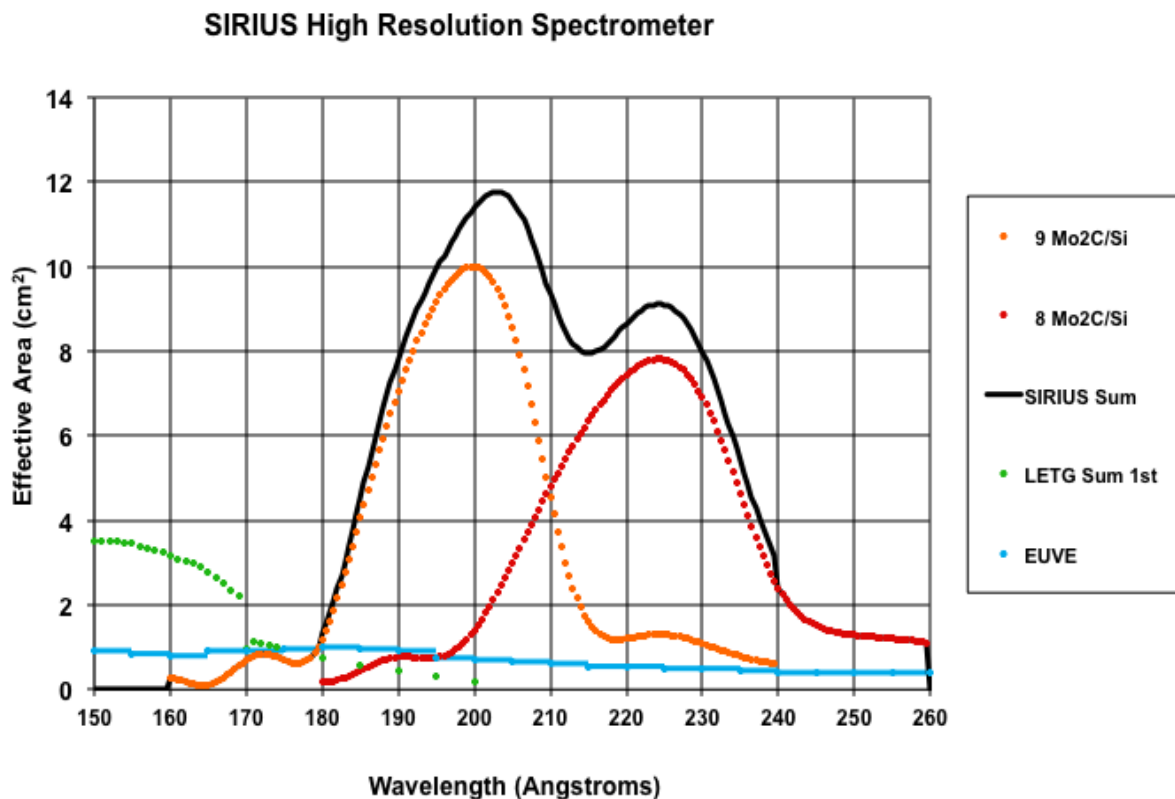


Figure 3. The effective area of SIRIUS, showing the individual wavebands, with Mo₂C/Si coatings (orange and red), and the sum (black). The effective areas of Chandra LETG (green) and EUVE (blue) are shown for comparison.

Table 1. **Average** performance of each spectrograph component and the cumulative effective area for a single grating. The total effective area is a combination of the four gratings.

Spectrograph element	
Single grating area (cm ²)	143.0
Grating groove efficiency	0.508
Multilayer peak reflectance	0.295
Detector QE	0.35
Collimator transmittance	0.90
Al filter transmittance	0.55
Effective area per grating (cm²)	3.7

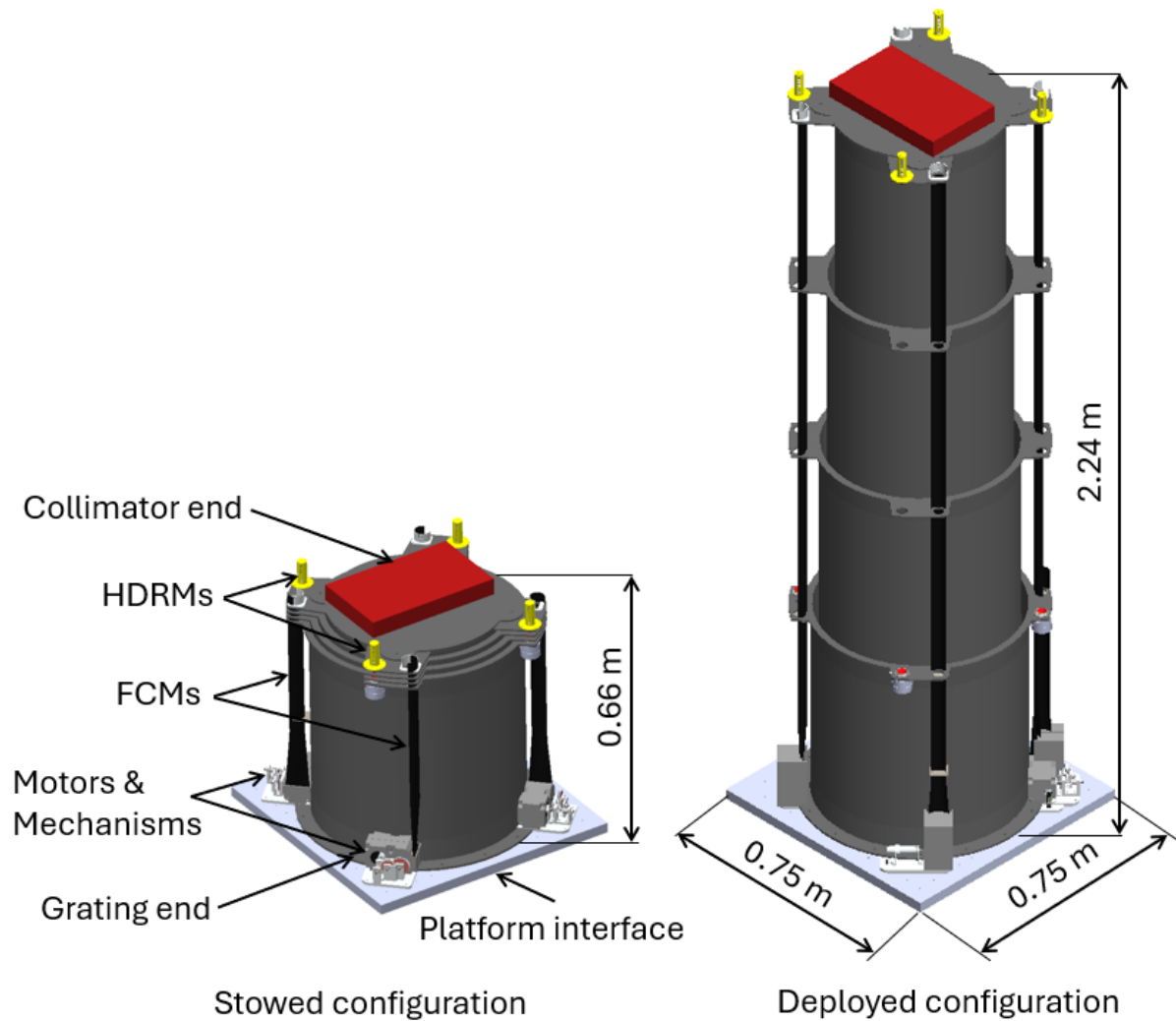


Figure 4. Diagram of a deployable optical bench structure, in stowed and extended configurations.

Spacecraft and other mission requirements

The mission requires a 3-axis stabilized spacecraft for operation in LEO and existing “off-the-shelf” spacecraft designs are being considered. During the UKSA study, we worked with BAE Systems to evaluate several spacecraft options from their catalogue. The baseline platform selected for the SIRIUS mission is the BAE Systems P30 platform. The P30 platform provides the core platform avionics, structure, electronics and software for the SIRIUS mission and can support a payload mass of approximately 70 kg. A wide range of interfaces are supported by its scalable CubeScale architecture, and appropriate compatible COTS equipment is selected to meet the performance requirements of a specific mission, thereby providing a high TRL reliable and cost-efficient route to orbit. The object grating spectrograph (i.e. no slit) has modest pointing needs, with an accuracy (APE) of ~ 1 arcmin and 1 arcsec stability (RPE) on target. By upgrading the baseline AOCS solution the BAE Systems P30 can support the pointing and attitude stability requirements of the mission and will include a thruster for orbital maneuvers and to ensure compliance with deorbit requirements. The P30 follows a tailored ECSS process as per the F-Mini concept for lower cost missions. Much of the key equipment on the P30 platform has space heritage and the core avionics is flying on the Azalea Cluster-1 mission launched in November 2025. SIRIUS will have a Sun-avoidance angle $> 30^\circ$. The fixed solar arrays provide adequate power generation for pointing up to 60 degrees from the plane orthogonal to the Earth-Sun line. Therefore, all targets within an annulus of 30° to 150° in Sun angle will be accessible at any time. Science operations will require a maximum daily downlink of 1.2 Gb per day, easily achieved by 1 payload data X-band downlink session per day. Figure 5 shows the P30 spacecraft with the OSS deployable spectrograph structure. The key parameters of the mission are summarized in Table 2.

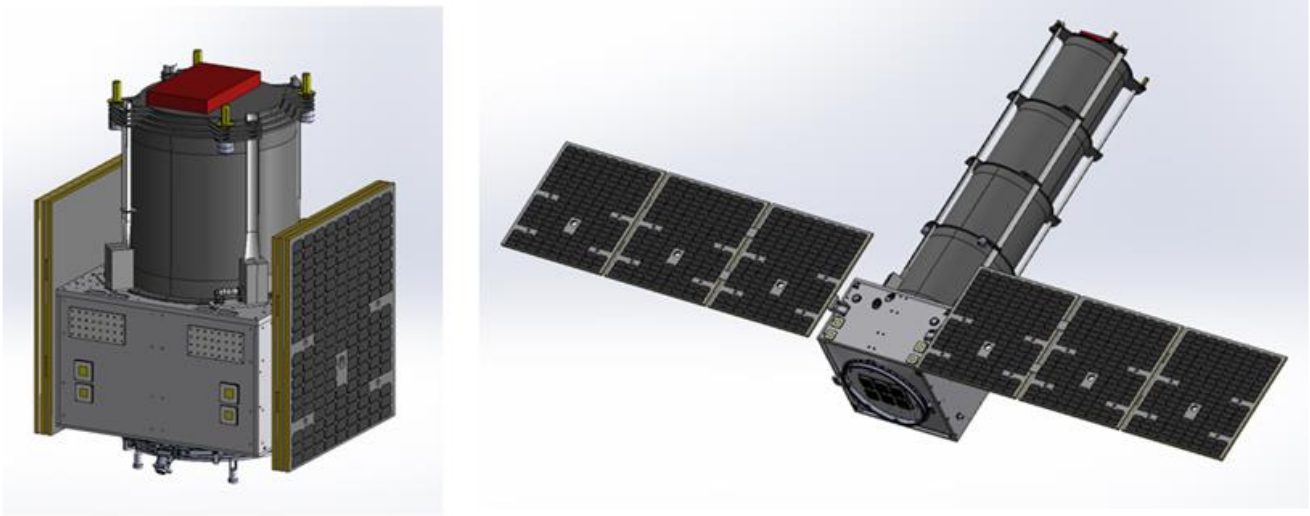


Figure 5. SIRIUS spacecraft in the stowed (left) and deployed (right) configuration

Table 2. Mission summary.

Category	Parameter
Launch Vehicle	TBD rideshare, compatible with Falcon 9
Trajectory Design	Science Orbit: LEO
Flight System	Design lifetime: 5 years, nominal mission 2 years Payload: single EUV spectrograph, mass: 70 kg, power: 30 W Observing mode: 3-axis control: pointing accuracy (APE): 1 arcmin; knowledge (AKE): 1 arcsec; stability (RPE): 1 arcsec/s Average science data acquisition rate: 20 kb/s
Spacecraft Bus	BAE Systems P30 (example), total spacecraft wet mass $< 320\text{kg}$
Data Return	1 X-band payload data downlink session per day
Power	2 arrays of 3 panels, ave. orbit power generation $> 200\text{W}$, ave. orbit usage $< 125\text{W}$
Propulsion	Electric propulsion

Mission Costs

Order of magnitude mission costs were determined during the UKSA phase 0 study. Since the project is technically mature and the payload makes modest demands on the spacecraft, launch services and mission operations, we have a high degree of confidence that the costs can be maintained well within a total £50M cost envelope. The estimated mission costs, based on a detailed bottom-up re-costing, informed by J-PEX flight experience, are £47M.

5. CONCLUSIONS

We have presented the design of a high resolution ($R \sim 5000$) EUV spectrograph capable of studying white dwarfs, stellar coronal sources and the local interstellar medium. The science goals focus on understanding the environments in the local region of our galaxy, within 100-200pc of the Sun, which can impact significantly on planetary systems orbiting other stars and affect their habitability. The effective area of SIRIUS is around a factor 10 larger than past and present observatories such as the EUVE spectrograph and Chandra Low Energy Transmission Grating, albeit over a narrower wavelength range. However, the wavelength coverage can be tuned and optimized to specific science goals. Therefore, this work shows that, by applying multi-layer coatings to normal incidence optics, SIRIUS can deliver observatory class capability traditionally delivered by large grazing incidence systems.

In comparison with large facilities such as Chandra, SIRIUS is clearly classed as a small space mission. However, its 2-m focal length requires a dedicated or, at best, a dual payload launch keeping it in the cost bracket for NASA SMEX or ESA Fast missions at $\sim$ €200M. Nevertheless, we have explored methods to reduce costs further through a study funded by the UK Space Agency. Oxford Space Systems designed a telescope deployment system that allows the payload length to be reduced for launch, to 1/3 of the full length of the spectrograph. As an objective spectrometer design, the SIRIUS instrument has more relaxed pointing requirements than a conventional spectrometer with a slit, which usually requires sub arcsecond pointing and fine guidance during exposures. Working with BAE Systems, we were able to find an off-the-shelf solution for a spacecraft for SIRIUS which could deliver the required attitude control requirements with modest modifications. The small footprint of the spacecraft coupled with the deployment system allows the mission to use a multiple payload ride-share such as a Falcon 9.

Adopting the mission options identified in the recent study of SIRIUS, we have shown that the mission can be reduced significantly to $\sim$ £50M, which is a small fraction ($\sim$ 1/4) of conventional small mission options. Furthermore, we can do this without compromising the science outcomes. Therefore, SIRIUS can deliver observatory class science at very low cost.

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