ISM Mission Concept - DAYBREAK

Instrumentation

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CHANGE LOG FOR CURRENT ISSUE

Date	Issue	Revision	Section	Reason for change
19th September 2025	1	0	Instruments	Initial Issue

Contents

List of Figures

List of Tables

0 Supporting Documentation

0.1 Applicable Documents

The following documents are applicable to this analysis:

AD1 **DAYBREAK-EX-001** *(ISM Mission Concept - DAYBREAK (Executive Summary))*

AD2 **"Transforming Exploration of the Local Interstellar Medium using SmallSat Technology"** *Anthony Freeman, Mark Chodas, and Jamie Jasinski. (The 4S Symposium, 2024)*

AD3 **Decadal Survey** *The Next Decade Of Discovery In Solar And Space Physics Space Studies Board - National Academies of Sciences. 2025*

0.2 Reference Documents

The following documents were referenced during this analysis:

[1] T. Lennertz, "DAYBREAK-TL-001 : ISM Mission Concept - DAYBREAK (Communications)," M.S. thesis, University of Leicester, 2025.

[2] E. Gainey, "DAYBREAK-EG-001 : ISM Mission Concept - DAYBREAK (Power Systems)," M.S. thesis, University of Leicester, 2025.

[3] K. Auker-Howlett, "DAYBREAK-KAH-001 : ISM Mission Concept - DAYBREAK (Radiation)," M.S. thesis, University of Leicester, 2025.

[4] K. Thuvakaran, "DAYBREAK-KT-001 : ISM Mission Concept - DAYBREAK (Trajectory)," M.S. thesis, University of Leicester, 2025.

[5] P. Dickson, *Sputnik: The Shock of the Century.* Walker Publishing Company, 2001.

[6] A. Balogh et al., "Missions to Mercury," *Space Science Reviews*, vol. 132, pp. 611–645, 2007.

[7] D. Titov et al., "Missions to Venus," *Earth-Like Planets and Moons*, vol. 514, pp. 13–20, Sep. 2002.

[8] K. A. Farley et al., "Mars 2020 Mission Overview," *Space Science Reviews*, vol. 216, 2020.

[9] H. C. Dethloff and R. A. Schorn, *Voyager's Grand Tour.* Konecky & Konecky, 2009.

[10] A. J. Tatem, S. J. Goetz, and S. I. Hay, "Fifty years of earth observation satellites: Views from above have lead to countless advances on the ground in both scientific knowledge and daily life.," *American Scientist, 96(5), 390–398*, 2008.

[11] N. T. Bridges and B. L. Ehlmann, "The mars science laboratory (msl) bagnold dunes campaign, phase i: Overview and introduction to the special issue.," *Journal of Geophysical Research: Planets*, 2017.

[12] J. Kinnison, R. Vaughan, P. Hill, N. Raouafi, Y. Guo, and N. Pinkine, "Parker solar probe: A mission to touch the sun," *IEEE Aerospace Conference*, 2020.

[13] S. N. Borovikov and N. V. Pogorelov, "Voyager 1 near the heliopause," *The Astrophysical Journal Letters*, vol. 783, p. L16, 2014.

[14] D. J. McComas, W. S. Lewis, and N. A. Schwadron, "IBEX's enigmatic ribbon in the sky and its many possible sources," *Reviews of Geophysics*, vol. 52, pp. 118–155, 2014.

[15] M. I. Etchegaray, "Preliminary scientific rationale for a voyage to a thousand astronomical units," *Jet Propulsion Laboratory*, vol. 87-17, 1987.

[16] P. C. Brandt et al., "Interstellar probe: Humanity's exploration of the galaxy begins," *Acta Astronautica*, 2022.

[17] *Interstellar Probe Whitepapers & Publications*, Accessed: 2025-09-03. [Online]. Available: `https://interstellarprobe.jhuapl.edu/Resources/Publications/index.php`.

[18] *Pioneer 10 Sends Last Signal*, Accessed: 2025-09-03. [Online]. Available: `https://science.nasa.gov/missions/pioneer/pioneer-10-sends-last-signal/`.

[19] M. Zemcov et al., "Astrophysics with New Horizons: Making the Most of a Generational Opportunity," *The Astronomical Society of the Pacific*, 2018.

[20] G. H. Fountain et al., "The New Horizons Spacecraft," *Space Science Reviews*, 2008.

[21] S. A. Stern, H. A. Weaver, J. R. Spencer, H. A. Elliott, and the New Horizons Team, "The New Horizons Kuiper Belt Extended Mission," *Space Science Reviews*, 2018.

[22] *NASA Turns Off 2 Voyager Science Instruments to Extend Mission*, Accessed: 2025-09-03. [Online]. Available: `https://science.nasa.gov/blogs/voyager/2025/03/05/nasa-turns-off-2-voyager-science-instruments-to-extend-mission/`.

[23] M. Wall, *Trump's 2026 budget would slash NASA funding by 24% and its workforce by nearly one third*, Accessed: 2025-09-03. [Online]. Available: `https://www.space.com/space-exploration/trumps-2026-budget-would-slash-nasa-funding-by-24-percent-and-its-workforce-by-nearly-one-third`.

[24] D. G. Mitchell et al., "Imaging-neutral camera (INCA) for the NASA Cassini mission to Saturn and Titan," in *Cassini/Huygens: A Mission to the Saturnian Systems*, vol. 2803, SPIE, 1996, pp. 154–161.

[25] D. McComas et al., "IBEX—Interstellar Boundary Explorer," *Space Science Reviews*, 2009.

[26] A. Galli et al., "Callisto's Atmosphere and Its Space Environment: Prospects for the Particle Environment Package on Board JUICE," *Earth and Space Science*, vol. 9, no. 5, 2022.

[27] E. STONE, R. VOGT, B. T. F.B. McDONALD, J. TRAINOR, J. JOKIPII, and W. WEBBER, "COSMIC RAY INVESTIGATION FOR THE VOYAGER MISSIONS; ENERGETIC PARTICLE STUDIES IN THE OUTER HELIOSPHERE AND BEYOND," *Space Science Reviews*, 1977.

[28] H. Ahn et al., "The Cosmic Ray Energetics And Mass (CREAM) instrument," *Space Science Reviews*, 2017.

[29] S. Krimigis et al., "The Low Energy Charged Particle experiment on the Voyager spacecraft," *Space Science Reviews*, 1978.

[30] A. M. Galper et al., "The PAMELA experiment: A decade of Cosmic Ray Physics in space," *Journal of Physics: Conference Series*, 2017.

[31] G. D. Badhwar, "Martian Radiation EnvIronment Experiment (MARIE)," *Space Science Reviews*, 2004.

[32] S. Orsini et al., "Low energy high angular resolution neutral atom detection by means of micro-shuttering techniques: The BepiColombo SERENA/ELENA sensor," *AIP Conf. Proc.*, 2009.

[33] B. Reinisch et al., "The IMAGE mission and first observations from the radio plasma imager," in *2000 5th International Symposium on Antennas, Propagation, and EM Theory. ISAPE 2000 (IEEE Cat. No.00EX417)*, 2000, pp. 474–478.

[34] D. McComas et al., "The Two Wide-angle Imaging Neutral-atom Spectrometers (TWINS) NASA Mission-of-Opportunity," *Space Science Reviews*, 2009.

[35] N. A. Schwadron and D. J. McComas, "SPATIAL RETENTION OF IONS PRODUCING THE IBEX RIBBON," *The Astrophysical Journal*, 2013.

[36] J. Halekas et al., "The solar wind ion analyzer for MAVEN," *Space Science Reviews*, 2015.

[37] J. Sauvaud et al., "The IMPACT Solar Wind Electron Analyzer (SWEA)," *Space Science Reviews*, vol. 136, no. 1–4, pp. 227–239, 2008.

[38] R. Kallenbach, J. Geiss, G. Gloeckler, and R. von Steiger, "Pick-up Ion Measurements in the Heliosphere – A Review," *Astrophysics and Space Science*, 2000.

[39] B. H. Mauk et al., "The Jupiter Energetic Particle Detector Instrument (JEDI) Investigation for the Juno Mission," *Space Science Reviews*, 2013.

[40] D. F. Vogl et al., "In-flight calibration of the Cassini-Radio and Plasma wave Science (rpws) antenna system for direction-finding and polarization measurements," *JOURNAL OF GEOPHYSICAL RESEARCH*, 2004.

[41] D. Gurnett, W. Kurth, L. Burlaga, and N. Ness, "In situ observations of interstellar plasma with Voyager 1," *Science*, 2013.

[42] *RPWS Engineering Technical Write-up*, Accessed: 2025-09-19. [Online]. Available: `https://science.nasa.gov/mission/cassini/spacecraft/cassini-orbiter/radio-and-plasma-wave-science/rpws-tech/`.

[43] *Swarm*, Accessed: 2025-09-11. [Online]. Available: `https://earth.esa.int/eogateway/missions/swarm`.

[44] D. Crider et al., "Magnetic field draping around Mars: Mars Global Surveyor results," *Advances in Space Research*, vol. 27, no. 11, pp. 1831–1836, 2001.

[45] *Europa Clipper*, Accessed: 2025-09-11. [Online]. Available: `https://d2pn8kiwq2w21t.cloudfront.net/documents/Europa-Clipper-Fact-Sheet.pdf`.

[46] E. M. Wakefield and S. Billingsley, "Fluxgate Magnetometers," *Proceedings of the SPIE*, vol. 5090, pp. 194–203, 2003.

[47] M. H. Acuña, "Space-based magnetometers," *Review of Scientific Instruments*, 2002.

[48] L. F. Burlaga, N. F. Ness, and E. C. Stone, "Magnetic Field Observations as Voyager 1 Entered the Heliosheath Depletion Region," *Science*, vol. 341, no. 6142, pp. 147–150, 2013.

[49] K. W. BEHANNON, M. H. ACUNA, L. F. BURLAGA, R. P. LEPPING, and N. F. NESS, "MAGNETIC FIELD EXPERIMENT FOR VOYAGERS 1 AND 2," *Space Science Reviews*, 1977.

[50] M. G. Kivelson et al., "The Europa Clipper Magnetometer," *Space Science Reviews*, 2023.

[51] M. H. Acuña, "THE DESIGN, CONSTRUCTION AND TEST OF MAGNETICALLY CLEAN SPACECRAFT - A PRACTICAL GUIDE," Goddard Space Flight Center, Tech. Rep., 2000.

[52] J. Connerney et al., "The Juno Magnetic Field Investigation," *Space Science Reviews*, 2017.

[53] J. M. L. H. Wm. S. West and H. Bilsky, "TECHNIQUES FOR ACHIEVING MAGNETIC CLEANLINESS ON DEEP-SPACE MISSIONS," NASA, Tech. Rep., 1971.

[54] *AXIOM: Advanced X-ray Imaging of the Magnetosphere*, Accessed: 2025-09-10. [Online]. Available: `https://www.mssl.ucl.ac.uk/~gbr/kirill/booms.html`.

[55] H. Zhang, Y. Zhang, C. Huang, Y. Yuan, and L. Cheng, *Spacecraft Magnetic Design and Test Technology*. Springer Singapore, 2020.

[56] W. Krenkel, *Carbon Fibre Reinforced Silicon Carbide Composites (C/SiC, C/C-SiC)*. Springer US, 2005, pp. 17–148.

[57] *Deflection of beams*, Accessed: 2025-09-12. [Online]. Available: `http://www.clag.org.uk/beam.html`.

[58] D. C. Miller, "The voyager magnetometer boom," JPL, Tech. Rep., 1979.

[59] *Interstellar Mission*, Accessed: 2025-09-13. [Online]. Available: `https://science.nasa.gov/mission/voyager/interstellar-mission/`.

[60] *Into the unknown! Interstellar adventure begins for Voyager 1*, Accessed: 2025-09-13. [Online]. Available: `https://www.rocketstem.org/2013/10/03/voyager-1-interstellar-adventure-begins/`.

[61] Z. Sternovsky, R. Mikula, M. Horanyi, J. Hillier, R. Srama, and F. Postberg, "Laboratory calibration of the Interstellar Dust Experiment (IDEX) instrument," in *AGU Fall Meeting Abstracts*, 2021.

[62] *Interstellar Dust Experiment (IDEX)*, Accessed: 2025-09-04. [Online]. Available: `https://imap.princeton.edu/spacecraft/instruments/interstellar-dust-experiment-idex`.

[63] *Media Library*, Accessed: 2025-09-19. [Online]. Available: https://imap.princeton.edu/public-media-library.

[64] A. Doner et al., "New Horizons Venetia Burney Student Dust Counter Observes Higher than Expected Fluxes Approaching 60 au," *The Astrophysical Journal Letters*, vol. 961, p. L38, Jan. 2024.

[65] M. Horanyi et al., "The Student Dust Counter on the New Horizons Mission," *Space Science Reviews*, vol. 140, pp. 387–402, Oct. 2008.

[66] *Design Testing*, Accessed: 2025-09-19. [Online]. Available: https://lasp.colorado.edu/sdc/instrument/design-testing/.

[67] E. C. Stone, "The Voyager Encounter With Uranus," *International Astronomical Union Colloquium*, 1982.

[68] C. Sagan, *Pale Blue Dot*. Random House, 1994.

[69] *20-Year Hubble Study of Uranus Yields New Atmospheric Insights*, Accessed: 2025-09-05. [Online]. Available: https://science.nasa.gov/missions/hubble/20-year-hubble-study-of-uranus-yields-new-atmospheric-insights/.

[70] J. M. Jasinski et al., "The anomalous state of Uranus's magnetosphere during the Voyager 2 flyby," *Nature Astronomy*, 2025.

[71] *Scientists Find a New Moon Orbiting Uranus*, Accessed: 2025-09-05. [Online]. Available: https://www.wired.com/story/new-moon-identified-on-uranus-orbiting-close-to-its-ring-system.

[72] *Voyager 1's Pale Blue Dot*, Accessed: 2025-09-19. [Online]. Available: https://science.nasa.gov/mission/voyager/voyager-1s-pale-blue-dot/.

[73] *Where are Voyager 1 and Voyager 2 Now?* Accessed: 2025-09-05. [Online]. Available: https://science.nasa.gov/mission/voyager/where-are-voyager-1-and-voyager-2-now/.

[74] *Pioneer 10*, Accessed: 2025-09-05. [Online]. Available: https://science.nasa.gov/mission/pioneer-10/.

[75] *Pioneer 11*, Accessed: 2025-09-05. [Online]. Available: https://science.nasa.gov/mission/pioneer-11/.

[76] *The Voyager Planetary Mission*, Accessed: 2025-09-05. [Online]. Available: https://science.nasa.gov/mission/voyager/fact-sheet/.

[77] *Galileo*, Accessed: 2025-09-05. [Online]. Available: https://science.nasa.gov/mission/galileo/.

[78] *Cassini Mission Overview*, Accessed: 2025-09-05. [Online]. Available: https://sci.esa.int/web/cassini-huygens/-/50203-cassini-mission-overview.

[79] *Juno*, Accessed: 2025-09-05. [Online]. Available: https://science.nasa.gov/mission/juno/.

[80] *New Horizons*, Accessed: 2025-09-05. [Online]. Available: https://science.nasa.gov/mission/New-Horizons/.

[81] C. Maccone, *Deep Space Flight and Communications: Exploting the Sun as a Gravitational Lens*. Praxis Publishing, 2009.

[82] *Instruments*, Accessed: 2025-09-19. [Online]. Available: https://imap.princeton.edu/spacecraft/instruments.

0.3 Terminology

The following terms recur throughout this document:

- **AU**: Astronomical Unit
- **CRS**: Cosmic Ray Subsystem
- **CME**: Coronal Mass Ejection
- **DC**: Dust Collector
- **ENA**: Energetic Neutral Atom
- **FOV**: Field of View
- **ISM**: Interstellar Medium
- **ISP**: Interstellar Probe
- **LISM**: Local Interstellar Medium
- **MAG**: Magnetometer
- **MSSL**: Mullard Space Science Laboratory
- **PUI**: Pick-Up Ion
- **PVDF**: Polarised Polyvinylidene Fluoride
- **PWA**: Plasma Wave Analyser
- **SDC**: Ventia Burney Student Dust Collector
- **SWA**: Solar Wind Analyser
- **C/SiC**: Carbon-Silicon Carbide
- **SWaP**: Low-Size, Weight and Power

1 Introduction

1.1 Personal Scope

The DAYBREAK mission is divided into five fundamental sections.These are Communication Systems [1] , Power Systems [2], Radiation Protection [3], Vehicle Trajectory [4] and Vehicle Instrumentation. Additional sections, comprising of Thermal Management, Attitude Determination and Control Systems, Alternate Trajectory, and Launch Dynamics, are managed by the international contingent of the team, and will be discussed in greater detail in DAYBREAK-EX-001. This report focusses on DAYBREAK's Instrumentation, particularly its Magnetometer. Over the duration of the mission development, as lead on the instrumentation package, I have overseen the selection of a payload that will enable DAYBREAK to answer the fundamental science questions established during the earliest phases of planning. Predominantly, this has been research based, as it quickly became clear that developing a new, bespoke instrument package was beyond the scope of DAYBREAK at this stage, as no lab space was accessible for mock-up designs, and design software is typically designed and kept in-house by missions. Therefore, the emphasis shifted to identifying pre-existing instruments that could meet the constraints outlined in Section 2. Thus, the bulk of the work comprised researching heritage and upcoming instruments, supported by detailed trade-off studies. Particular attention was given to magnetometers, identified as the most critical instrument for retention within the mission payload. Technical work on magnetometers concentrated on ensuring spacecraft magnetic cleanliness (9.3) and calculating the boom length required to minimise magnetic interference from the vehicle (9.4).

1.2 Mission Scope

Unmanned missions have advanced rapidly since Sputnik broadcast its first ′deep beep-beep′ on October 4th 1957 [5]. In the near seven decades since, Humanity has sent probes to each planet in the Solar System [6][7][8][9], monitored our own planet in unparalleled detail [10], navigated Martian dunes [11], and even skimmed the surface of the Sun [12]. But the very edges of the system we call home, remain elusive. Although in-situ measurements have been obtained, they originate from missions whose primary objectives were not centred around the Heliopause or the Local Interstellar Medium (LISM) [13] and have thus only scratched the very surface of the science in these regions. To emphasise how minimal this data potentially is, remote sensing of the region between the points that the Voyager missions crossed the Termination Shock revealed areas of increased Energetic Neutral Atom (ENA) emissions [14] that had gone undetected. Not only was this ′Ribbon′ previously undetected, it was neither simulated or theorised [14]. This indicates that there is a vast amount of science still waiting to be uncovered in this region. Although only limited in-situ data has been collected to date, missions to the Heliopause and beyond have been proposed, but none have yet been realised. Historically, ′TAU′ (Thousand Astronomical Units) was one such mission, with the main science drivers including in-situ measurements of the Heliopause and LISM [15]. However, TAU was quietly shelved during the 1990's and whilst it has not been possible to determine the reason for the cancellation through open access literature, it seems likely that the requirement for a ″1-MW nuclear-powered electric propulsion system″ requiring ″about 10 years of fuel″ [15], would be implausible today, let alone three decades ago. More recently, the Interstellar Probe mission has been proposed [16], although this is currently still within its planning phase, and there has been little in the way of development since 2022 [17]. Other missions that are due to cross the Heliopause include Pioneer 10, Pioneer 11, and New Horizons. Of the three, only New Horizons will have the possibility to gather new data, as Pioneer 11 ceased communications in 1995, and Pioneer 10 ceased communications in 2003 [18]. Even then, whilst New

Horizons does offer the opportunity to conduct ground-breaking science from the outer Solar System and beyond [19], it must be noted that the spacecraft itself was primarily developed with the goal of observing Pluto and its moons [20], and then later observing the Kuiper Belt [21], with its instrumentation therefore not being finely tuned for specific Heliospheric processes. Therefore, momentarily at least, our exploration continues to be reliant on the rapidly decreasing abilities of the Voyager program, which is due to shutdown in the 2030's [22].

DAYBREAK intends to change this current approach. With NASA's latest decadal survey identifying the boundaries of the Heliosystem as a key target [AD3], the opportunity now exists for a mission specifically designed to fill the knowledge gaps surrounding what occurs at the Heliopause and in the LISM. DAYBREAK is a mission designed as a direct consequence of this latest decadal survey. Based upon the proposal by Freeman, Chodas, and Jasinski [AD2], DAYBREAK is designed to be a small, fast, and lightweight package, reaching 200 AU in as few as 35 years, crossing through the Heliopause en-route. With its design being based on heritage instruments that require updates to modern standards, rather than complete re-designs, not only will it simplify production, but decrease development costs at a time where NASA faces enormous financial pressures [23]. It will be the first deep-space mission to be powered with Americium, rather than Plutonium, to take advantage of the extended half-life (432 and 88 years respectively) [2] of Americium, and will benefit from improved communication systems currently in development on Earth [1]. DAYBREAK therefore stands as the flagship for a new dawn in Heliospheric science missions: small, ambitious, practical, and cost-effective, without sacrificing scientific potential.

2 Science Goals

As discussed in 1.2, none of the in-situ measurements taken at the Heliosphere have derived from spacecraft whose primary mission was the Heliopause or the LISM. As DAYBREAK will be the first mission to explicitly explore and document this area, it's mission goals serve as the overriding motivation for its design. These goals ask the following questions:

- **P.1**: "What are the key properties of the Heliosphere and how does it interact with the ISM?"
- **P.2**: "What is the nature of the plasma, magnetic, and radiation environments with the ISM?"
- **C.1**: "What is the origin and behaviour of the Ribbon?"
- **C.2**: "How does space weather change across the Solar System up to the Heliopause and how does it interact with it?"
- **C.3**: "What is the nature of the solar interactions with the outer planetary systems?"

P.1 and P.2 are primary goals. These are the questions that drive the development of DAYBREAK, and closely align with the targets laid out in AD3. C.1, C.2, and C.3, are cruise-phase goals, which DAYBREAK will answer on its journey toward the Heliopause and LISM. Each overarching goal is made up of specific objectives, which address individual parts of the goal. These objectives are discussed in greater detail in AD1, but are summarised in tables below:

All of these objectives are combined to form a science matrix (AD1). This matrix informed the DAYBREAK team as to the specific measurements required to achieve the overarching questions, and inform design and payload choices.

Ref	Focus	Key Measurements and Outcomes
P.1: "What are the key properties of the Heliosphere and how does it interact with the ISM?"		
P.1.1	Heliopause Shape	Resolve competing shape theories by combining in-situ magnetic/plasma field measurements (∼0.01-10 nT) with ENA imaging from ∼100-200 AU.
P.1.2	Transport & Heating	Explain the slowing yet overheating of the solar wind, via direct measurements of solar wind (0.1-10 keV), pick-up ions (1-100 keV), and pressure balance.
P.1.3	Anti-Sunward Leakage	Identify how Heliospheric ions cross the boundary, by detecting and mapping the direction of 40-139 keV ions, near the termination shock and Heliopause.
P.1.4	Bow Shock	Determine the structure of the Bow Shock, by measuring changes in He^+, to constrain current models.
P.1.5	Hydrogen Wall	Map interstellar H between ∼100-200 AU, to determine density and thickness.

Table 1: Science Goal 'P.1' Objectives

Ref	Focus	Key Measurements and Outcomes
P.2: "What is the nature of the plasma, magnetic, and radiation environments of the ISM?"		
P.2.1	ISM Plasma Composition	Address Voyager-observed ion density step-ups (∼140-143 AU). Measure major ions (H^+, He^+) and pick-up ions across ∼10 eV-10 keV; obtain the first clean, direct interstellar H measurement.
P.2.2	Radiation Environment (GCRs)	Quantify GCR spectra outside Heliospheric shielding.
P.2.3	Anomalous Cosmic Rays (ACRs)	Identify mechanisms in pick-up ions, such as their turbulence, reconnection, and termination-shock interaction processes, that cause ACRs.
P.2.4	Solar Disturbances in the LISM	Study CME driven magnetic oscillations beyond the Heliopause, characterising how LISM conditions modify these disturbances and how they modulate GCRs and the local environment.

Table 2: Science Goal 'P.2' Objectives

Ref	Focus	Key Measurements and Outcomes
C.1: "What is the origin and behaviour of the Ribbon?"		
C.1.1	Cause	Determine whether the Ribbon arises from secondary ENAs linked to LISM magnetic fields, or from other Heliospheric boundary processes.
C.1.2	Influence of Interstellar Wind	Quantify how variations in the interstellar wind change the Ribbon's energy distributions and size.
C.1.3	Particle Characterisation	Measure ENA spectra and composition in the ∼0.2–6 keV range, identifying ion species and potential source populations to constrain the Ribbon's origin.

Table 3: Science Goal 'C.1' Objectives

Ref	Focus	Key Measurements and Outcomes
C.2: "How does space weather change across the Solar System up to the Heliopause, and how does it interact with it?"		
C.2.1	Evolution	Determine how CMEs, the Solar Wind, and GCRs evolve with with distance, and how solar activity helps to shape the Heliopause
C.2.2	ACR/GCR Flux and spectra	Determine how solar cycles, Heliospheric boundaries, and local interstellar conditions modulate ACR and GCR levels with distance from the Sun.
C.2.3	Solar Wind Evolution	Determine solar wind speed, density, and composition, to establish how Heliospheric conditions evolve with distance and set boundary conditions at the Heliopause.

Table 4: Science Goal 'C.2' Objectives

Ref	Focus	Key Measurements and Outcomes
C.3: "What is the nature of solar interactions with the outer planetary systems?"		
C.3.1	Planetary Magnetosphere Structure	Map outer planets during flybys to resolve boundary structure and dynamics.
C.3.2	Charged-particle transfer via solar wind	Characterise how solar wind particles interact with planetary magnetospheres by mapping low energy populations (10-40,000 eV/q) and high-energy species (30 keV to > 1 MeV).

Table 5: Science Goal 'C.3' Objectives

3 Instruments

3.1 Identifying Legacy Instruments

Having determined DAYBREAK's overarching science goals (2), it became possible to develop a corresponding set of desirable instrumentation. These instruments were identified as those most capable of translating the mission objectives into achievable outcomes. Each of them are able to answer multiple questions, supporting other instruments in their operations, and providing a well rounded approach to task. For example, by selecting a Magnetometer, an ENA Imager, and a Plasma Wave Analyser, all three can work in harmony to map large scale structures, such as the Bow Shock, and the Heliopause, fulfilling the requirements of P.2 (Table 2), and C.2 (Table 4). Each instrument therefore captures a different angle of the same question, helping build up detailed models as DAYBREAK extends along its flight path. Before the individual instruments could be decided upon however, the first step was to conduct background research into the different systems and which missions they were attached to, as it didn't seem appropriate to select a package without first understanding the context in which the instrument was placed. For example, it would not be appropriate for DAYBREAK to select a magnetometer with excellent values, only to discover it was designed for a 6-month Earth-orbit mission, had no flight-heritage, and had yet to be put into production, over a magnetometer system that had slightly marginal values, but had a proven history with deep-space missions. This wide-angle, context-based approach to research provided an abundance of candidate instruments as multiple missions had instruments that showed potential matches to the requirements of DAYBREAK. However, the availability of information for each instrument varied considerably, complicating direct comparisons. This disparity is illustrated in Table 6, where INCA and IBEX parameters were readily accessible, whereas those for the imager onboard JUICE proved exceptionally difficult to obtain. Broadly, such inconsistencies fell into two categories: in some cases (e.g. JUICE), the instrument was sufficiently new that few technical publications were available; in others, the instrument was sufficiently old that relevant data had either been lost or never digitised.

Mission	Mass (kg)	Power (W)	Data Rate	Range	Source
INCA	8.5	26.1	<10 kpbs	<10 keV - 8 MeV	[24]
IBEX	7.37	3.5	102.6 -122.8 bps	0.01 - 6 keV	[25]
JUICE	-	-	-	0.5 keV – 5 MeV	[26]

Table 6: Disparity in Data for Historical ENA Instruments

During the search for legacy instruments, both Voyager spacecraft were looked at closely, partly for their flight heritage, but predominantly for their longevity and careful mission management. Even though the instruments themselves were designed for a planetary tour [9], their designs proved to be robust enough to survive a mission far beyond their anticipated lifetimes, which was of great interest to DAYBREAK. New Horizons was also considered in great depth, as it is the most modern mission that is due to exit the Heliopause, and therefore represents the closest approximation to the type of mission that DAYBREAK aims to fulfil. All of the missions and instruments researched for this study are listed below in Table 7.

Table 7: Research Instruments and Missions

Instrument Category	Mission* or Specific Instrument†
MAG	Messenger*, Clipper*, Voyager*, Cassini*
PWA	Voyager*, Polar*, Cassini*
SWA	MAVEN*, STEREO *, PESA-H/L†, THEMIS *, STATIC†, SWE†, IMAP*
CRS	Voyager*, PAMELA*, MARIE†, ISP CRS†
ENA	INCA†, IBEX*, TWINS*, IMAGE*, JENI†, IMAP-Lo†, IMAP-High†, IMAP-Ultra†
PUI	PEPSSI†, JUNO*, SWA-I†, PLASTIC†,EPI-Lo†, PAN†
DC	IDEX†

It should be noted, however, that whilst legacy instruments were prioritised, they were not the only avenue explored for the DAYBREAK instrument package. Consideration was also given to commercially available "off-the-shelf" instruments. Unlike legacy hardware, these products are typically accompanied by comprehensive specification sheets, reflecting the commercial interest that supports their development. Nonetheless, it was quickly determined that no currently available package was suitable for DAYBREAK, as existing offerings are primarily designed for Earth-orbiting missions rather than the demands of a deep-space operation. Using an off-the-shelf package as a baseline development tool for a DAYBREAK specific instrument was beyond the scope of this phase of development.

3.2 Selecting Instruments

With a pool of instruments to now choose from, the next step for DAYBREAK was to determine which were most suitable for onwards selection. To facilitate this, a comprehensive trade-off analysis was conducted, and each trade-off saw multiple iterations to test different priorities for each instrument package. The instrument-specific trade-off studies are provided in the relevant sections within this document (4.2 through 9.2). To achieve these trade-off studies, a pairwise weighting approach was adopted, consistent with established multi-criteria decision analysis techniques such as the Analytic Hierarchy Process. This framework ensures that decisions are transparent, reproducible, and aligned with the mission's overarching science goals. Because instrument selection involves trade-offs across multiple criteria such as mass, power consumption, data rate et cetera, direct comparison of raw values would risk bias and inconsistency. To address this, all parameter values were first normalised to a common scale between zero and one. This was done through the following expression:

$$x_{\text{norm}} = \frac{x - \min}{\max - \min} \tag{1}$$

For parameters such as FOV, where higher values were advantageous, the instrument with the smallest value was assigned one, the instrument with the largest value was assigned zero, and intermediate instruments were scaled proportionally between them. For criteria where lower values were preferable, such as mass and power, the scaling was inverted so that the lowest value scored zero and the highest scored one. Each criterion was then assigned an importance value on a scale of 1 - 10, with lower numbers representing higher priority. These importance ratings were converted into weights by taking their inverse and then rescaling them so that the weights across all criteria summed to one. Each instrument's score for a given criterion was then multiplied by the weight of that criterion, and the weighted scores were summed across all criteria to provide an overall suitability score. Although such rankings are sensitive to the chosen weights, the pairwise weighting method provided a repeatable framework for exploring trade-offs and ensuring that final instrument selection was aligned with both technical feasibility and DAYBREAK's scientific objectives. Data availability varied for each instrument, with parameters that were indeterminable being marked in black. Once trade-off was complete, values that were selected to be taken into the final decision making process were highlighted in green. This helped a visual record to be kept of the trade-off process. Whilst only the final values are shown for each instrument, the below example of the PWA (Section 8.2) trade-off highlights the background method applied to each instrument. By dividing the column weight with the importance factor, the normalisation value could be determined. The overall weighting could then be determined from the row sum being divided by the row total.

Importance	(1 = High, 5 = Average, 10 = Not At All)							
	Power	**Mass**	**Data Rate**	**Range**	**Min Freq**	**Max Fre**	*Row Total*	
Power	5	5	5	1	1	1	18	
Mass	5	5	5	1	1	1	18	
Data Rate	5	5	5	1	1	1	18	
Range	1	1	1	1	1	1	6	
Min Frequency	1	1	1	1	1	1	6	
Max Frequency	1	1	1	1	1	1	6	
Clm Wt Total:	18	18	18	6	6	6	72	*Row Sum*

Figure 1: Importance Values

	Normalisation					(Importance/Weight Total)
	Power	**Mass**	**Data Rate**	**Range**	**Min Freq**	**Max Fre**
Power	0.278	0.278	0.278	0.167	0.167	0.167
Mass	0.278	0.278	0.278	0.167	0.167	0.167
Data Rate	0.278	0.278	0.278	0.167	0.167	0.167
Range	0.056	0.056	0.056	0.333	0.333	0.333
Min Frequency	0.056	0.056	0.056	0.167	0.167	0.167
Max Frequency	0.056	0.056	0.056	0.167	0.167	0.167

Figure 2: Normalisation Values

Power	0.25
Mass	0.25
Data Rate	0.25
Range	0.083333333
Min Frequency	0.083333333
Max Frequency	0.083333333
	1

Figure 3: Weighting Values

4 Cosmic-Ray Subsystem

4.1 Purpose and Function

The Cosmic-Ray Subsystem is designed to detect energetic particles that originate from solar and galactic sources. These rays can be divided into two groups: Galactic (GCR) and Anomalous (ACR). GCRs are high-energy particles originating from outside the Solar System, and ACRs are ionised neutral atoms which have interacted with the Heliosphere and have been accelerated to very high energies. Measuring their spectra and composition informs models of particle acceleration and transport mechanisms, sheds light on the modulation of GCRs by solar and Heliospheric magnetic fields, and constrains the coupling between the Heliosphere and the LISM. These measurements link closely with the requirements of DAYBREAK's P.2, (Table 2), and C.2 (Table 4) questions. To detect these rays, CRSs use layers of silicon detectors, arranged to measure the differential energy loss and residual energy of incident particles. This allows determination of their charge, mass, and energy over a wide dynamic range [27]. CRS instruments provide the necessary observational capability to address DAYBREAK's fundamental questions concerning cosmic-ray origins, acceleration, and transport, thereby contributing essential measurements for understanding Heliospheric physics and its coupling to the broader galactic environment.

4.2 Trade Off Analysis

Trade-off analysis for this subsystem proved exceptionally difficult. Despite the range of missions and instruments available for study, very few quantifiable parameters were available in open access literature. Historically, CRS instruments are ground-based monitors, or balloon-mounted instruments [28], with very few systems being flown in Space. Of this pool, even fewer have been outside of an Earth orbit, and only the Voyager missions have seen a CRS reach distances similar to those that

DAYBREAK will reach. Further, as seen in Table 8, only Voyager possessed meaningful data. The ISP mission has yet to be developed, MARIE possessed very few published parameters, and PAMELA was an Earth orbiting mission with the benefits of a large system able to be supported by solar arrays. Therefore, adopting the Voyager CRS as the baseline provided the only realistic direction for DAYBREAK, with no trade-off necessary.

Mission	Mass (kg)	Power (W)	Data Rate	Range	Record Rate	Source
Voyager	7.4	4.2	250 bps	15 keV - 40 MeV (Min) 300 - 500 MeV (Max)	Cruise: 25.6 Minutes Encounter: 3.2 Minutes Special: 1.6 Minutes	[29]
PAMELA	470	355	-	< 1.2 TeV	-	[30]
MARIE	-	-	-	15 - 500 MeV	-	[31]
ISP	8	7	1 kbps	10MeV - 1GeV	-	[16]

Table 8: Data for Historical CRS Instruments

5 Energetic Neutral Atoms

5.1 Purpose and Function

ENAs arise when charged particles collide with neutral atoms, with the collision removing the charge from the initial particle, making it also neutrally charged. Detection is typically achieved through ENA imagers, which convert the neutral atom back into an ion on a thin surface, followed by energy per charge and time of flight analysis to determine its energy and species [32]. ENA imagers have historically been highly successful, with the IMAGE mission's Low (LENA), Medium (MENA), and High (HENA) band imagers producing the first global maps of Earth's ring current, revealing the dynamic processes that occur during geomagnetic storms [33]. Building on this, the TWINS mission provided stereoscopic ENA observations from two spacecraft in high-altitude elliptical orbits, enabling full reconstruction of Earth's magnetospheric structure [34]. Most recently, the Interstellar Boundary Explorer (IBEX) extended ENA imaging to the Heliosphere, detecting emissions from the Heliosheath and revealing the unexpected "IBEX ribbon", a narrow band of enhanced ENA flux thought to trace interactions between the solar wind and the local interstellar magnetic field [35]. This unexpected Ribbon is a key driver for the inclusion of an ENA imager onboard DAYBREAK, as it will build on the questions left unanswered from IBEX's discovery, and is the sole question posed by C.1, as seen in Table 3.

5.2 Trade Off Analysis

Trade-off for this system had unique permutations. Whilst instrument fundamentals such as mass, power, and time of operation can be easily assessed against one another, other factors such as FOV, range, and angular resolution, prove trickier. To navigate this, the values were weighted towards those with the broadest values. For example, the full sky coverage provided by IMAGE's 90 x 360°FOV was preferred over the narrower band of 120 x 90°FOV of INCA, and the 10 keV - 3 MeV detection range of INCA being preferred over the extremely limited range of 0.01 - 6 keV held by IBEX. Ultimately, the IMAGE system was selected for use in DAYBREAK. Primarily, the system held the most useful parameters for answering the objectives laid out in Table 3. It's large FOV allows the entire structure of the Ribbon to be observed, and its angular resolution allows for mapping in the greatest detail. Further, it conducts its science in pulses of 2.7 seconds, allowing for the fast capture of a large field. This can help map subtle changes in the Ribbon as DAYBREAK passes through. The actual design of the system came into play too, as IMAGE was comprised of a Low (LENA), Medium (MENA), and High (HENA) band imager. Upgrades to these will allow for an even greater spectrum of energies to be covered. The trade-off for ENA imagers also revealed an aspect that had yet to be factored into the decision making values. JENI is a modern instrument (onboard JUICE), but very few technical details were available in open access literature, and thus it was discounted. Whilst IBEX was not selected (due to its very narrow detection range, and small FOV), it was the most modern instrument subjected to trade-off with available data. Given that the design philosophy for DAYBREAK currently centres around upgrading heritage instruments to modern standards, here was a case where a modern instrument needed minimal alteration to be the preferential choice. Therefore, any future work would be better placed around the minimal upgrading of the IBEX system to cover a larger range of energies, rather than the heavy upgrades required for the IMAGE system.

	Power (W)			Mass (kg)			Data Rate (kbps)		
	Value	Normalised	Weighted	Value	Normalised	Weighted	Value	Normalised	Weighted
INCA	8.5	0.00	0.00	26.1	1	0.257	10	0.1984	0.05
IBEX	12.09	0.29	0.08	3.5	0.00	0.00	0.1	0.00	0.00
TWINS	18.7	0.83	0.21	25.3	0.96	0.25	50	1.00	0.26
IMAGE	20.75	1.00	0.26	22.5	0.84	0.22	44	0.88	0.23
JENI				5.5	0.09	0.02			

	Range			FOV (°)			Time (Seconds)			Angular Resolution (°)		
	Value	Normalised	Weighted	Value	Normalised	Weighted	Value	Normalised	Weighted	Value	Normalised	Weighted
INCA	10 keV - 3 MeV	0.598	0.034	120 x 90	0.332	0.019	360	1	0.01	4 x 4	0.234	0.013
IBEX	0.01 - 6 keV	0	0.000	6.5 x 360	0.071	0.004	0.0042	0	0.00	6.5 x 6.5	0	0.000
TWINS	1 - 100 keV	0.019	0.001	70	0	0.000	60	0.16657	0.00	4 x 4	0.234	0.013
IMAGE	10 eV - 500 keV	0.099	0.006	90 x 360	1	0.057	2.7	0.00738	0.00	8	1	0.057
JENI	0.5 keV - 5 MeV	1	0.057									

Figure 4: ENA Trade-Off

6 Solar Wind Analysers

6.1 Purpose and Function

Solar Wind Analysers (SWA) are designed to measure the properties of the solar wind's plasma, including its constituent ion and electron densities, temperatures, velocities, and distribution functions. Typically SWAs use electrostatic analysers that select particles of specified energies by deflecting them through curved electric fields and directing them towards microchannel plates for particle counting [36]. By sweeping through voltage ranges and measuring particle fluxes, these instruments can build three-dimensional velocity distribution functions of solar wind ions and electrons. By doing this, SWAs provide the essential plasma context needed to interpret energetic particle, field, and remote-sensing observations, while also constraining models of solar and planetary interactions, and space weather phenomena. Therefore, they have a major role to play onboard DAYBREAK, as P.1 (Table 1) C.2 (Table 4), and C.3 (Table 5), all look to determine the nature and interactions of the solar wind.

6.2 Trade Off Analysis

Solar Wind Analysers were another subsystem for which trade-off proved problematic. The vast majority of systems had few, if any, technical parameters available, making a comprehensive analysis difficult. Only MAVEN, and IMPACT possessed significant enough data to be analysed. Their parameters are defined below in Table 9. Whilst IMPACT possesses an attractive array of measurement parameters, it was the enhanced energy detection range of MAVEN that became the deciding factor. As DAYBREAK is building on historic science, and traversing an area that is poorly categorised, the ability to capture a broader range of particle energies is essential. A wider dynamic range not only ensures sensitivity to the core solar wind ions, but also transient ions that may otherwise be missed. By maximising potential coverage, DAYBREAK can better characterise the variability of the solar wind and its coupling to planetary environments, thereby reducing observational gaps and enabling a more comprehensive test of existing Heliospheric models.

Mission	Mass (kg)	Power (W)	Data Rate	Resolution	Energy Range	FOV(°)	Source
MAVEN	2.62	1.75	604 bps	14.5%	5.1 eV - 26 keV	360 x 90	[36]
IMPACT	0.97	0.55	534	-	1 eV - 3 keV	360 x 120	[37]

Table 9: Data for Historical SWA Instruments

7 Pick-Up Ions

7.1 Purpose and Function

Pick-Up Ion (PUI) detectors are specialised plasma instruments designed to measure ions that originate as neutral atoms, become ionised in the Heliosphere, and are subsequently "picked up" and accelerated by the solar wind's convective electric field. Similarly to ENA imagers (5.1), these detectors combine energy per charge analysis with time of flight, to determine ion energy, mass, and composition across a wide dynamic range. Of particular interest to DAYBREAK, is that PUIs stemming from interstellar gas are now recognised as a key mechanism in the creation of ACRs [38]. These findings demonstrate that PUIs serve as a fundamental link between exospheric processes and Heliospheric particle acceleration, making their detection critical for cosmic ray physics. PUI detectors therefore overlap with multiple of DAYBREAK's science objectives, making them a crucial choice for the payload.

7.2 Trade Off Analysis

Instrument parameters were once again poorly constrained for this trade-off, with only PEPSSI (New Horizons), having data available in every category. On initial inspection, it seems therefore, to be a logical choice for selection, due to its low power and mass being closely aligned with DAYBREAK's SWaP philosophy and possessing exemplary flight heritage. However, this does not provide the clearest picture of the data. For example, the mass of JEDI (part of the JUNO mission), is stated as 6.4 kg. However, 5 kg of that mass is radiation shielding to protect the instrument for a long period mission in the Jupiter environment [39]. As DAYBREAK is only in this region for <8 days [4], less shielding will be required [3], and thus this mass becomes more aligned to the SWaP philosophy. Further, other data needs to be placed in the context of their host mission. For example, PEPSSI was attached to New Horizons, and thus would have had a limited data link due to the ranges in which it was operating. JEDI, orbiting as part of JUNO around Jupiter, has no such issues, and can successfully command a higher data rate. With lessons learnt from the ENA trade-off (Figure 4), range was taken as the sum of the largest detection point, minus the lowest detection value. Whilst JADE only has a small range (0.05 - 100 keV), it is this minimum value that proves useful for DAYBREAK. By increasing the detection chances with an enhanced range, models can be built up in greater detail. The range also does not represent the constituents. Whilst JEDI offers the greatest range, this is broken into bands of ions. For example, its detection range of H+ spans from 10 - 2000 keV, but its band for O/S extends from 45 - 10000 keV [39]. This highlights the importance of having a large detection range, to try and capture as many ions as possible. As a result both JADE and JEDI were selected as DAYBREAK's baseline instruments, under a single 'JUNO' entry. Their combined range potential, FOV, and Resolution situate them as the most applicable instruments for DAYBREAK's science objectives.

	Power (W)			Mass (kg)			Data Rate (bps)		
	Value	Normalised	Weighted	Value	Normalised	Weighted	Value	Normalised	Weighted
PEPSSI	2.55	0.00	0.00	1.5	0.00	0	91	0	0
JADE	[redacted]			5.2	0.76	0.169	[redacted]		
SWAPI				3	0.31	0.068			
PLASTIC									
JEDI	3.1	1.00	0.22	6.4	1.00	0.224	16000	1	0.224

	Range (keV)			Resolution (ΔE)			FOV (°)			Interval (s)		
	Value	Normalised	Weighted	Value	Normalised	Weighted	Value	Normalised	Weighted	Value	Normalised	Weighted
PEPSSI	975	0.090	0.007	14	0.000	0.000	160 x 12	0	0.000	0.00000032	0.000	0.000
JADE	99.95	0.002	0.0002	28	1.000	0.082	360 x 90	1	0.082	1.000	1.000	0.082
SWAPI	99.8	0.002	0.0002	[redacted]								
PLASTIC	79.7	0.000	0.0000									
JEDI	9990	1.000	0.0824	26.700	0.907	0.075	160 x 12	0	0.000	[redacted]		

Figure 5: PUI Trade-Off

8 Plasma Wave Analysers

8.1 Purpose and Function

Plasma Wave Analysers (PWAs) are designed to measure the electric and magnetic field fluctuations, plasma conditions and wave–particle interactions generated by plasma waves across a wide frequency spectrum. These instruments are typically built around electric field antennas and, in some cases, magnetic search coils, which feed into receivers and spectrum analysers to resolve both broadband waveforms and narrowband emissions. Historically, PWAs are incredibly successful instruments.The Cassini Radio and Plasma Wave Science (RPWS) utilised three orthogonal electric monopoles, three magnetic search coils, and a Langmuir probe to measure fields from a few Hz up to 16 MHz, enabling direction-finding, polarisation analysis, and density/temperature diagnostics of Saturn's plasma environment [40]. Further the Voyager PWA has operated continuously since launch, measuring plasma wave activity from a few Hz to tens of kHz, and famously used the change in plasma oscillation it detected to determine that the mission had breached the Heliopause and entered the LISM [41]. Therefore, plasma wave measurements are critical for probing fundamental plasma processes, identifying regions of particle acceleration, and mapping the large-scale structure and dynamics of planetary magnetospheres and the Heliosphere. This supports DAYBREAK's science objectives closely, and was a key driver for the instruments selection.

8.2 Trade Off Analysis

The PWA trade-off analysis identified a clear winner once considered in the broader mission context. While the low power consumption and mass of Voyager's plasma wave subsystem aligned well with the SWaP philosophy being applied to DAYBREAK, it was the wide detection range of Cassini's RPWS that led to its selection as the baseline instrument. Voyager's plasma wave data was the determining factor for understanding the mission's transition into the LISM, and Cassini's increased sensitivity across multiple frequency bands provides enhanced capability to constrain models of this region, directly supporting DAYBREAK's science objectives. Concerns regarding the high data rate (900 bps) were alleviated by research showing that this figure refers to the cumulative output of the full RPWS instrument suite [42]. Therefore, the effective rate attributable to the antenna subsystem alone is expected to be significantly lower, and thus pose less problematic for DAYBREAK's duty cycles [2].

	Power (W)			Mass (kg)			Data Rate (bps)		
	Value	Normalised	Weighted	Value	Normalised	Weighted	Value	Normalised	Weighted
Voyager	1.6	0.00	0.00	1.4	0.00	0	32	0.026152517	0.006538129
Casinni	7.00	1.00	0.25	3.8	1.00	0.25	900	1.00	0.25
Polar	[redacted]						8.69	0.00	0

	Range (dB)			Minimum Frequency (Hz)			Maximum Frequency (Hz)		
	Value	Normalised	Weighted	Value	Normalised	Weighted	Value	Normalised	Weighted
Voyager	140	1	0.083333333	10	1	0.083333333	56200	0	0
Casinni	[redacted]			1	0.090909091	0.007575758	1250000	0.0748755	0.006239625
Polar	100	0	0	0.1	0	0	16000000	1	0.083333333

Figure 6: PWA Trade-Off

9 Magnetometers

9.1 Purpose and Function

Magnetometers have been utilised in nearly every mission type in the last sixty years. From Earth observation [43], to ambitious planetary surveys [44], and even missions hoping to enhance the search for life beyond Earth such as NASA's Europa Clipper [45], magnetometers have been a dependable and useful tool in the exploration of our Solar System. Their rugged and simplistic designs are a key contributor to their enduring utility. Their primary function is to measure and record the magnetic environment surrounding the spacecraft, and whilst most magnetometer data comes from planetary environments, it is also possible to capture ambient background fields. Within DAYBREAK's scope will be measurement of this ambient background field, to better understand how our Heliosphere interacts with the galactic magnetic field. For ease, when referring to the spacecraft's specific system, the acronym 'MAG' will henceforth be used. A Fluxgate magnetometer was selected for use on DAYBREAK, as will be discussed in 9.2. Fluxgates work by exploiting the magnetic response of a ferromagnetic core in order to detect an external magnetic field. The core material has a very high magnetic permeability, allowing the instrument to generate measurable signals when the core is driven into magnetic saturation. This saturation occurs, because a drive coil is wrapped around the core, which carries an alternating current, enabling it to cyclically saturate the core in opposite polarities.

In the absence of an external field, the magnetic responses from each saturation cancel exactly.

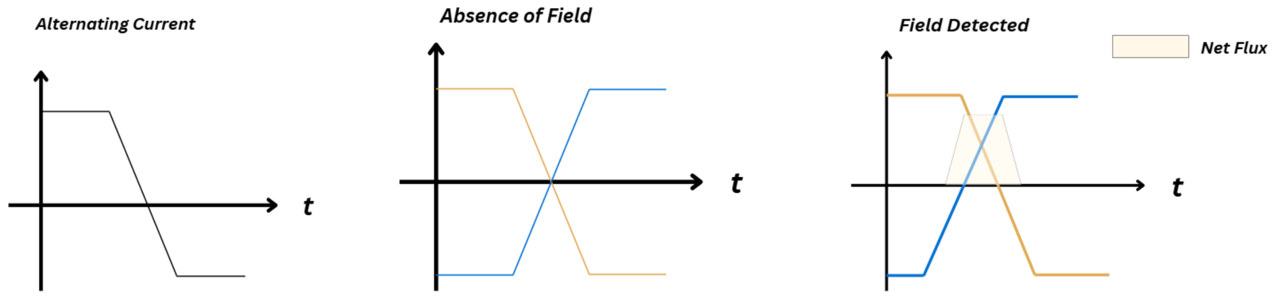

Figure 7: External Field Introducing Bias Towards Polarity

A secondary sense coil encircling the core detects the net magnetic flux. With perfect symmetry, no voltage is induced in the sensing coil. However, when an external magnetic field is present, this symmetry is broken. The external field biases the saturation cycle, shifting the permeability response of the cores, and as a result, the magnetic flux through the sensing coil no longer cancels [46]. This can be shown through Faraday's Law, whereby the equation below shows how the time-varying flux ($d\Phi$) induces the electromotive force:

$$\mathrm{EMF} = -\frac{d\Phi}{dt} \tag{2}$$

Because bias has been introduced, a voltage is now detected in the sensing coil. This is seen in Figure 7. Crucially, this induced voltage contains harmonic components of the drive frequency, the strongest of which occurs at twice the drive frequency. Signal processing electronics filter out this second harmonic component, whose amplitude is directly proportional to the strength of the external magnetic field, while its phase encodes polarity. This output is then converted into a digital or analogue signal representing the local magnetic field's strength and direction. Because of this, fluxgates can provide highly stable and sensitive measurements, making them ideal for space applications.

9.2 Trade Off Analysis

As highlighted in the previous section, a fluxgate magnetometer was selected for use aboard DAYBREAK. However, this only shows a small part of a larger decision making process. As a first step, the sensor type needed to be selected from one of two categories: vector or scalar. Scalar sensors measure the overall magnitude of the surrounding magnetic field, without regard to its direction. In contrast, vector magnetometers provide an output that reflects both the strength and the orientation of the magnetic field, referenced to a principal axis of the sensing element. Crucially though, scalar sensors only obtain useful signals for ambient fields larger than 20,000 nT and only if the local spatial field gradient is small [47]. Because of this, only vector sensors were deemed applicable for use aboard DAYBREAK, as Voyager 1 discovered that some areas of the Heliopause have a field strength of only 0.4 nT [48], far below the minimum requirement for scalar sensors. The specific type of vector sensor was the next parameter to constrain. As seen in Table 10, there are numerous variants of vector sensors, each with their own merits. Some, such as modern SQUID (Superconducting Quantum Interference Device) sensors, are able to operate with class leading levels of clarity in their measurements, with almost no noise infiltration. However, SQUID suffers from its necessity to operate with large cryogenic coolers, its overall high power demand and fragile construction, making it unsuitable (at its current stage of development) for space missions. Other sensors, such as the GMI (Giant Magneto-impedance), are easily overwhelmed by noise, and their accuracy suffers. Only one of the sensor types offered performed consistently well: the fluxgate. Not only does it have attractive parameters, but fluxgate sensors hold proven and extensive flight heritage, making their selection a logical choice for DAYBREAK.

Sensor	Noise	Power	Accuracy	Dynamic Range	Survivability	Size
Fluxgate	Excellent	Low-Moderate	Good	Wide	Good	Medium
AMR	Fair	Low	Poor	-	Good	Small
GMR	Poor	Low	Poor	-	Good	Small
GMI	Poor	Low	Poor	Wide	Good	Small
SDT	Fair	Low	Poor	-	Good	Small
Hall Effect	Poor	Low	Poor	-	Good	Small
SQUID	Excellent	High	Fair	Narrow	Lab Only	Large

Table 10: Comparison of Different Sensor Types [46]

However, it is important to note that fluxgate sensors themselves can have multiple core types, and therefore a further selection process took place. The three types of most interest to DAYBREAK were the ring, the rod, and the racetrack [46]. Ring cores are the most widely used sensor due to their ease of manufacture, robust design and survivability, low power consumption, and relatively low noise, making them ideal when low power and noise are the primary concerns, as is the case with DAYBREAK. Rod/Förster core sensors are preferred when resistance to cross-field effects are more important than noise performance and Racetrack core sensors have largely been replaced by Single Domain sensors, which offer better noise performance and easier fabrication [46]. Due to the way in which they closely match DAYBREAK's low power and low noise requirements, ring cores were chosen for onward use. A visual example of the three core types can be seen in Figure 8 below.

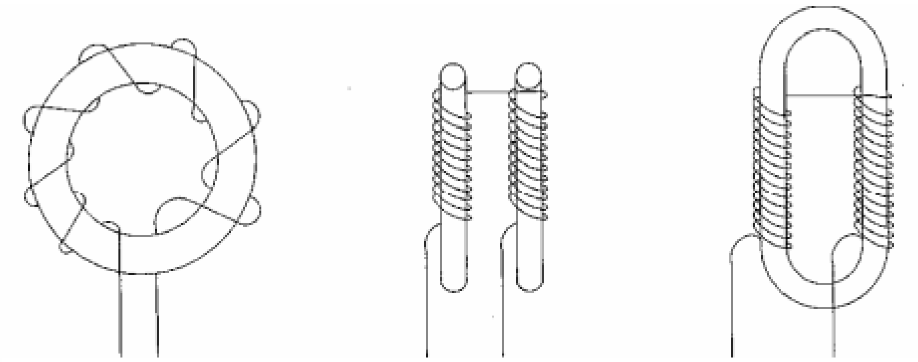

Figure 8: Common Magnetometer Core Types (*L-R: Ring, Rod, Racetrack Cores*)

Image Credit: E.M. Wakefield and S.W. Billingsley [46]

With a ring core fluxgate sensor chosen, the next step in developing the DAYBREAK MAG was to identify the most suitable legacy instrument to serve as its foundation. As outlined in 1.2, designing a fully bespoke magnetometer lay beyond the scope of this study phase, making the adaptation and upgrade of an existing instrument the preferred approach. Table 7 lists the missions reviewed for their magnetometer systems: Messenger, Europa Clipper, Voyager, and Cassini. Although Messenger may appear to be an outlier due to its trajectory towards the inner Solar System, given that its magnetometer would be designed to withstand the harsh conditions around Mercury it was included for potential survivability advantages. It was felt that this experience could offer valuable lessons for an extended mission such as DAYBREAK, where environmental damage such as radiation is a cumulative [3] process, and longevity needs to be actively built into the instrument. Regardless of which design was to be selected as the baseline for the bespoke DAYBREAK MAG, the number of magnetometers to be deployed remained an important consideration. Most missions employ a dual magnetometer configuration, with one instrument positioned at the outboard end of their boom and the other placed closer to the spacecraft. An example is provided by Voyager 1 and Voyager 2, which each carried two magnetometers: one mounted at the boom's outboard end and the other located at approximately 57% of the distance between the spacecraft body and the outboard sensor [49]. Both Voyagers utilised a hybrid system, with a further two sensors placed on the booms support structure [47]. Alternatively, modern missions such as Europa Clipper, have adopted a triple system, increasing both the redundancy and sensitivity of the system [50]. The addition of a third sensor improves characterisation of the magnetic field along the full length of the boom, thereby enabling more precise subtraction of spacecraft generated background noise.

As described in 3.2, a comparison table was compiled using parameters from the aforementioned missions. Two iterations of the trade-off analysis were conducted, prioritising low mass in the first and instrument performance in the second. These qualities, instrument accuracy and low mass, were identified as the most desirable traits for adaptation to the DAYBREAK mission. The results of this trade-off can be seen in Figure 9 (low mass priority), and Figure 10 (Instrument accuracy).

	Boom Length (m)			MAG (kg)			Other Mass (kg)		
	Value	Normalised	Weighted	Value	Normalised	Weighted	Value	Normalised	Weighted
Cassini	11	0.71	0.20	3	0.53	0.15	6.8	0.08	0.02
Clipper	8.5	0.47	0.13	1.3	0.21	0.06	27.4	0.63	0.18
Messenger	3.6	0.00	0.00	0.184	0.00	0.00	3.9	0.00	0.00
Voyager	14	1.00	0.28	5.5	1.00	0.28			

Figure 9: Magnetometer trade-off, prioritising low mass

	Power (W)			Range (G)			Resolution (nT)		
	Value	Normalised	Weighted	Value	Normalised	Weighted	Value	Normalised	Weighted
Cassini	3.1	0.00	0.00	13	0.00	0.00	0.005	0.00	0.00
Clipper	16.9	1.00	0.06	4000	1.00	0.06	0.008	0.07	0.00
Messenger	4.2	0.08	0.004	1530	0.38	0.02	0.047	1.00	0.06
Voyager	3.2	0.01	0.00	0.5	0.00	0.00	0.01	0.12	0.01

Figure 10: Magnetometer trade-off, prioritising instrument performance

In the low mass trade-off, the Messenger mission performed best. This outcome is expected, as its boom length was the shortest of the missions considered, inherently reducing overall mass. The category "other mass" includes electronic cabling, instrument housings, and features such as radiation shielding; however, the availability of this data varied across missions, with cabling weight being the only parameter consistently reported. In the instrument performance trade-off, Cassini and Voyager achieved the highest scores across all three evaluation categories. This presented an interesting outcome, as Europa Clipper had initially been expected to emerge as the preferred legacy instrument, given its status as the most modern of the missions reviewed. In the low mass trade-off however, it does score joint highest (alongside Cassini) if Mercury is removed as an outlier because of its short boom. Overall, the analysis shows that no single legacy instrument dominates across all categories, highlighting the need to balance mass constraints against instrument performance in selecting the baseline for DAYBREAK. A combined approach that integrates advantageous elements, such as Cassini's low power requirements, Europa Clipper's three magnetometer configuration, and

Voyager's proven structural resilience offers the clearest pathway for a DAYBREAK optimised MAG. Nevertheless, if a single legacy instrument were to be adopted without modification, Europa Clipper provides the most suitable baseline owing to its modern architecture, lightweight sensors, and excellent combined resolution and range values.

9.3 Magnetic Cleanliness

Modern magnetometers are highly sensitive, meaning that even small background fields generated by a spacecraft can distort measurements. To mitigate this, two approaches are utilised: using non-magnetic or low-magnetic materials in spacecraft construction, and mounting magnetometers on booms to increase their distance from interference sources. Despite careful design of batteries, motors, wiring, and other components to minimise stray fields, achieving the level of magnetic cleanliness required for high-accuracy missions remains extremely challenging. Since it is practically impossible to eliminate spacecraft-generated fields entirely, sensor placement on extended booms is standard practice, exploiting the rapid decrease of magnetic field strength with distance ($1/r^3$, where r is the distance to the source). Alongside sensor placement, material selection is fundamental to achieving magnetic cleanliness. Structural components are typically constructed from aluminium alloys, which are inherently non-magnetic and well suited for spacecraft frameworks and instrument housings [51]. Composite materials, such as carbon fibre–reinforced polymers, are also widely used (particularly for booms), because they provide excellent stiffness-to-mass properties while further reducing the risk of stray fields associated with conductive metals. For example, the Juno spacecraft employed a carbon–silicon carbide composite boom [52]. Conversely, materials with high magnetic permeability, such as conventional steels, should be avoided wherever possible. For smaller spacecraft parts such as bolts, aluminium or magnesium is preferred in place of ferromagnetic alloys [53]. All of these lessons will need to be applied to DAYBREAK, to give the MAG sensors the cleanest possible environment.

9.4 Magnetometer Booms

As highlighted in 9.3, one way to mitigate the magnetic noise seen by a MAG, is to place it on an extended boom away from the main spacecraft. The length to which the MAG needs to be held away is entirely unique to each mission, and thus must be calculated accordingly. Initial hopes were placed on the boom length equation provided by the Mullard Space Science Laboratory (MSSL) [54]. This follows as such:

$$L = \sqrt{a^2 + \frac{D^2}{16} \tan\left(\frac{x}{2}\right)} \tag{3}$$

Where the spacecraft is assumed to be hexagonal in shape, with a diameter D, and height a. The FOV of the MAG is represented by x. The example provided by MSSL, called for $D = 1.3$ metres, $a = 2.1$ metres, and a FOV of 30°. This would provide a value of 38 cm as the minimum boom length for a spacecraft of this size. To verifying the equation, it was recreated using Microsoft Excel. Unfortunately, this did not provide a matching answer, with the calculation producing a boom length of 1.32 metres. Thus, the equation was not taken forward for further use as it was unverifiable. Instead a new methodology was developed, based on modelling the magnetic field distribution of the spacecraft. This approach was implemented in Python, and by adopting this method, the results could be reproduced and systematically adapted for different mission configurations, offering a more robust alternative to the earlier equation. The outputs of this modelling process are presented in Figure 11, which shows the magnetic field of DAYBREAK.

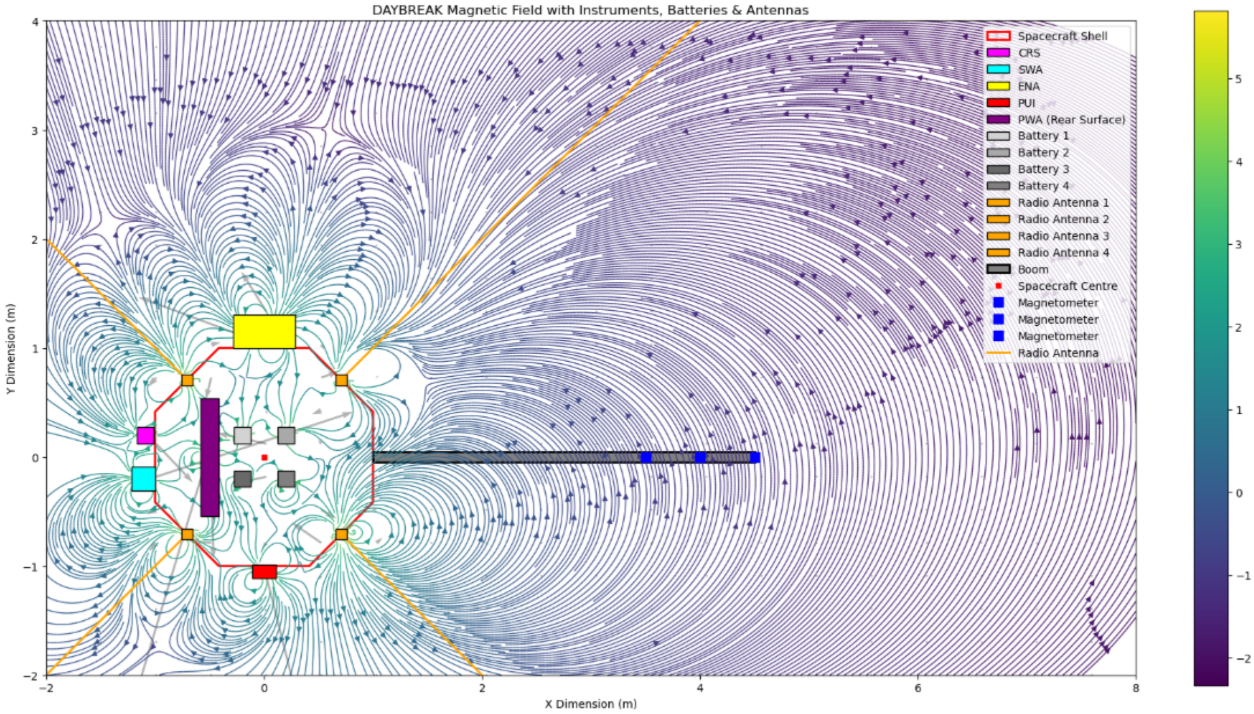

Figure 11: DAYBREAK's Magnetic Field

This field is the sum of each instrument, as they were modelled as individual dipoles, with this quasi-static model neglecting magnetic coupling. Such a setup is appropriate for the Direct Current and low-frequency contamination levels typically generated by spacecraft [55]. This setup is not without issue however, as DAYBREAK would need a bespoke software program in order to calculate its magnetic fields in greater details. As illustrated in Figure 12, the Europa Clipper employed a custom software package and physical modelling to generate a detailed map of the fields produced by approximately 400 dipole sources on the spacecraft.

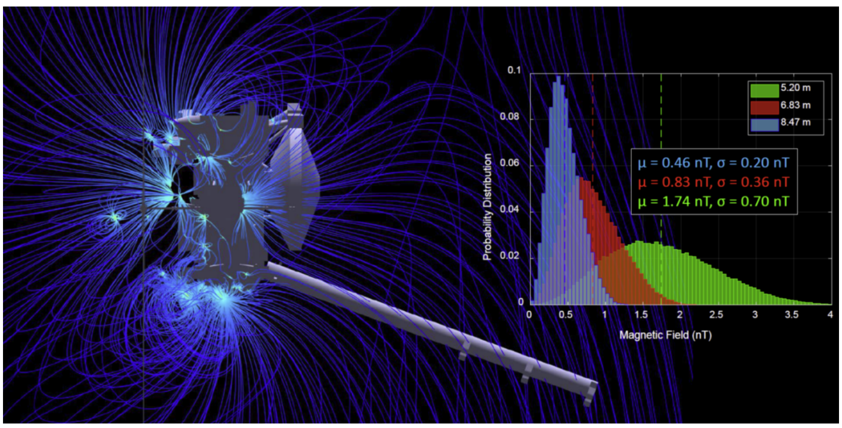

Figure 12: Magnetic Sources of the Europa Clipper

Image Courtesy: Kivelson et al. [50]

By mapping the baseline magnetic field of DAYBREAK, it becomes possible to determine the boom lengths at which spacecraft-generated noise is sufficiently reduced. For this analysis, the threshold was defined as the point where the magnetometers registered a residual field of 0.00 nT. This reflects the original science requirement (2) for a sensor to be able to detect a magnetic field of only 0.01 nT: any background contribution would otherwise obscure the measurements. The modelling was implemented using a forward Monte Carlo simulation in which the magnetic moments of the instruments were randomised 10^5 times, consistent with the approach adopted for the Europa Clipper study [50]. The randomisation occurs through, and is built into the Python model with:

$$B(r) = \frac{4\pi\mu_0}{|r|^5}(3rr^T - |r|^2 I)m \tag{4}$$

This model was generated with two variations, one model accounting for three MAGs, and the other with just two. Such variation was purposely done to determine if any mass savings (from a reduced boom length) could be found by using a reduced number of MAGs. In both variations, the MAGs were placed at the end of a 3.5 metre boom, with this short length intentionally placing the MAGs in areas of intense field. By doing this, and increasing the length in 10 cm increments, the noise reduction can be plotted onto a defined curve, with the point of 0.00 nT being mapped readily. In each Figure, Magnetometer 1 is the MAG closest to the spacecraft, therefore experiencing the highest interference. For the 2 MAG configuration, Magnetometer 2 is mounted on the end of the boom, and in the 3 MAG configuration, Magnetometer 3 is the end mounted device. This explains the different levels of flux they experience, as the field depletes at $1/r^3$. The results of these two variations are seen below. Figure 13 and Figure 14 show how the two MAG layout achieved a noiseless environment after 8 meters. Figures 15 and 16 highlight how the three MAG layout only achieved the noiseless environment after 9.3 m. This is likely due to the 50 cm spacing between the MAG sensors, which starts from the outboard end of the boom. The third MAG, being much closer to the spacecraft, will receive a higher interference than those at the end, so must be moved a greater distance out to ensure the total noise level read by all three MAGs becomes low enough to reach the specification determined by Section 2.

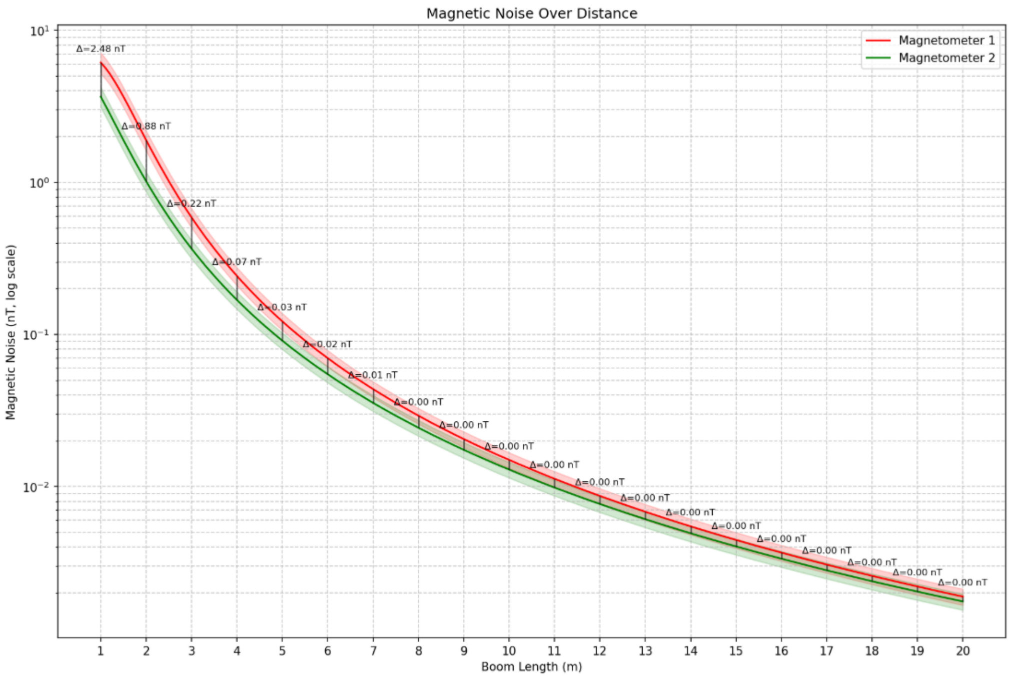

Figure 13: Magnetic Noise vs Boom Length (2 MAG)

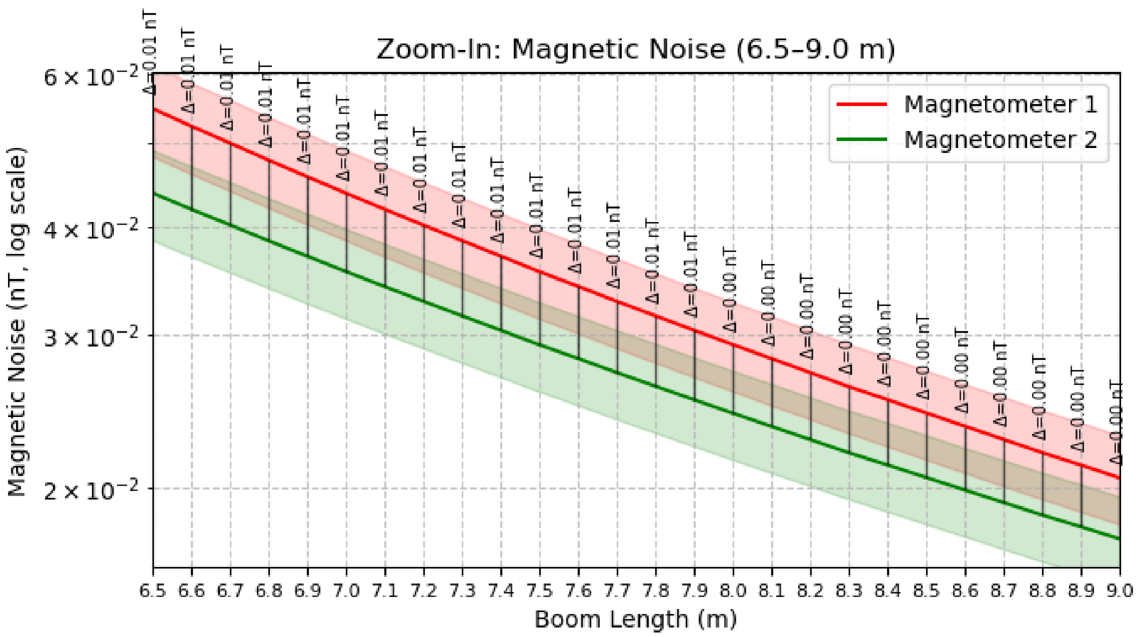

Figure 14: Magnetic Noise Reduction for 2 MAGs - Zoomed

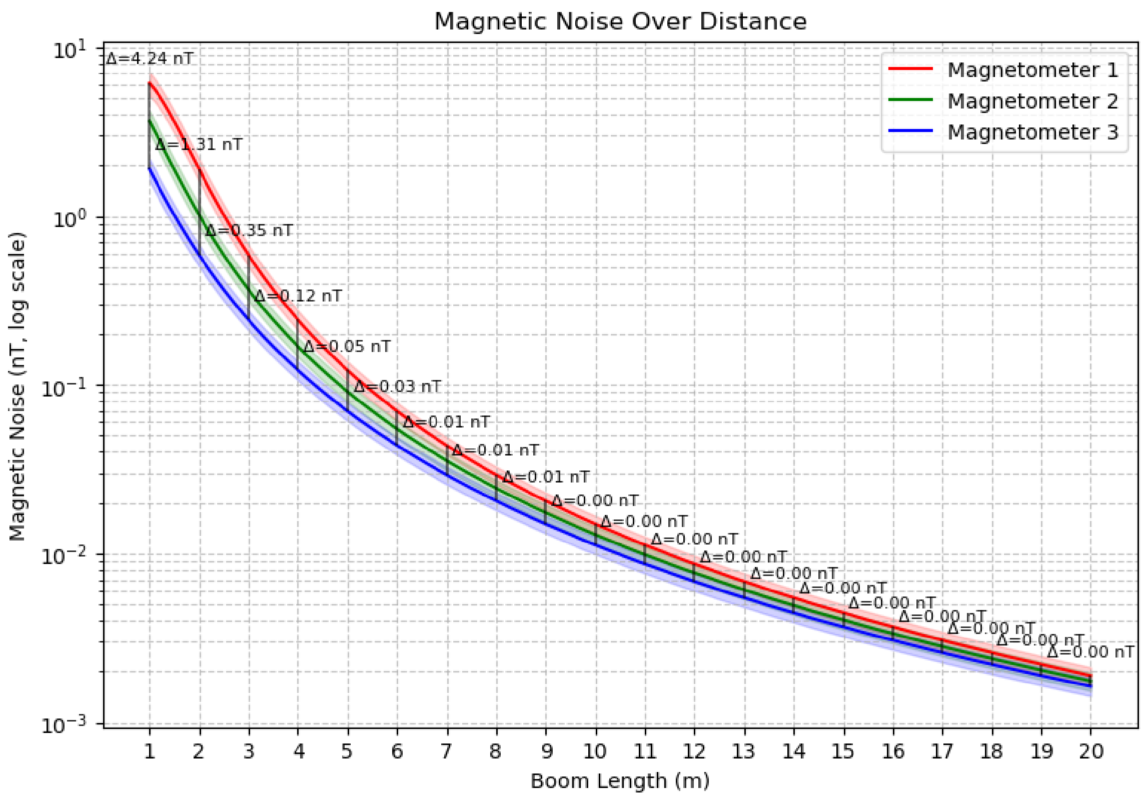

Figure 15: Magnetic Noise vs Boom Length (3 MAG)

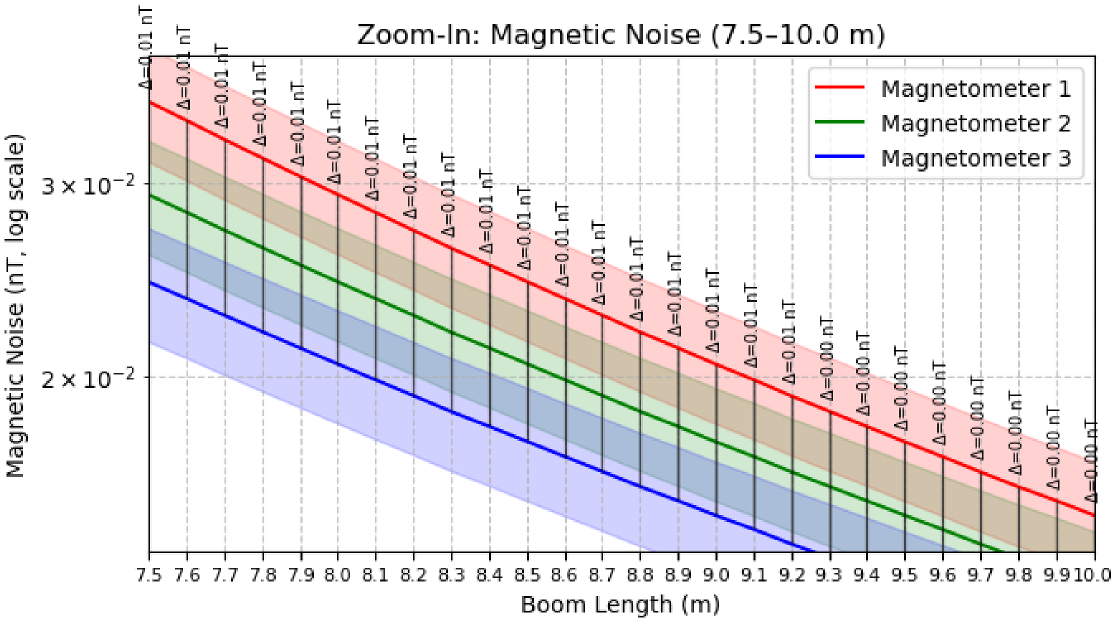

Figure 16: Magnetic Noise Reduction for 3 MAGs - Zoomed

Whilst the Python script provided an initial estimate of boom length, this value cannot be considered definitive, as uncertainties remain without bespoke magnetic cleanliness modelling. In line with DAYBREAK's margin policy (AD1), a 25% margin was applied. Although this margin is primarily used for mass, it was deemed appropriate to extend its application to geometric design in order to maintain consistency across subsystems and to allow for a safe margin that can be constrained in future iterations. This is also inline with the policy laid down in AIAA Standard S-120-2006e II-1. Applying this margin increases the two-MAG boom length from 8 m to 10 m, and the three-MAG boom length from 9.3 m to 11.63 m. As shown by its shorter required boom length, the advantage of running with a two MAG setup, is that the overall mass of the boom is greatly reduced. Booms are typically made of carbon composites, and taking C/SiC as an example, this has a density of 2.1 g/cm^3 [56]. A reduction in length of 1.63 metres allows for a significant weight saving. However, this benefit does not outweigh the additional redundancy, and greater accuracy of a three MAG setup. Being better able to map the exact field that the MAG sensors are experiencing, especially in a low ambient field plays more into the driving science of DAYBREAK.

The boom length allows us to calculate other properties of the boom, such as it's deflection under load, to see how it copes structurally in flight. In the diagram below, it can be seen that the angle of deflection is calculable through:

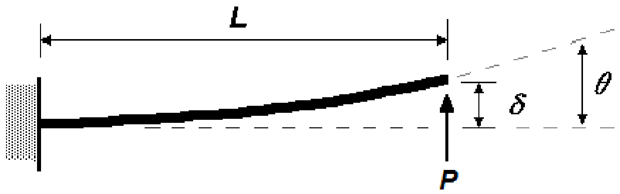

Figure 17: Beam Deflection

Image Courtesy: Russ Elliott [57]

Where:

$$\theta = \frac{PL^2}{2EI} \tag{5}$$

and,

$$I = \frac{\pi r^4}{4} \tag{6}$$

P represents the load on the free end of the boom, L is the length of the boom, E is the Young's modulus of the material, and I is the second moment of area of the boom's cross section [54]. r is the radius of the boom cross section, assuming it is cylindrical. P can be calculated as $F = M \cdot g = 3(1.3) \cdot 9.81$. Therefore P equals 38.26 N. This value assumes only the weight of three Europa Clipper magnetometers (1.3 kg each [50]) are acting on the boom, and that no cabling or instrument housings are present. Selecting a non-magnetic C/SiC material for boom, this has a Young's Modulus of 90 - 100 GPa [56] if it is of high quality construction. To account for potential manufacturing impurities, a conservative value of 90 GPa has been adopted. Given that the diameter of the Europa Clipper boom is 87 cm [50], this provides $I = 0.0281\ m^4$. Substituting these values, the angular deflection is:

$$\theta = \frac{38.26 \cdot (11.36)^2}{2 \cdot 90^9 \cdot 0.0281} \tag{7}$$

This provides a result of $9.5 \cdot 10{-}^8$ radians, equating to $5.410{-}^6$ degrees. This deflection is negligible and therefore poses no structural concern. Whilst this value is extremely promising, it makes large assumptions of parameters such as the load enacting on the boom, and its provision by the MSSL [54] raised questions over its validity, given that the MSSL boom length equation was unverifiable. A further assumption, is that this boom is one continuous, solid beam, which is very rarely the case for spacecraft. Instead, multiple types are available to selected. Simple booms best describe continuous beams, and these are simple to make to any desired length, but they cannot be stowed during launch. For this reason, they were discounted for use on DAYBREAK, as the fairing does not have the capacity to contain an 11.36 m boom. One way to circumvent this issues is to attach hinges at varying lengths down the boom arm, which allows for stowage before launch. However, these hinged booms require latches to be held in place, and if these fail to release, then the MAG would simply be stuck in an unusable position. Even if the latch does release correctly, the deployment is uncontrolled, with the boom having potential to snap back into its original position, or not lock into its correct position. For this reason, they were discounted. Telescopic booms offered more potential for DAYBREAK, as they can reach good lengths whilst having a smooth, controlled deployment, but they are untested for deep-space missions, where others, such as the coilable boom, provide a clear and longstanding history. Coilable booms can achieve great lengths with their controlled deployment, whilst being incredibly lightweight. They offer other advantages such as being retractable (should the MAGs need to be protected for any reason), and their flight heritage has shown excellent reliability [58]. They are similar in concept to ′tape measure′ booms, which can reach even greater lengths, but these have no discernable heritage. Therefore, a coilable boom was selected for use aboard DAYBREAK. A summarised flow-down of this decision process is seen in Figure 18.

To assess MAG performance, a new simulation was created. Within this, DAYBREAK's external environment was modelled as a stable magnetic field, with an increase in magnitude after 121.6 AU, the point that Voyager 1 crossed the Heliopause [59]. The DAYBREAK field model (Figure 11), was loaded into this environment and at each distance sample on the X-axis, the spacecrafts interaction with the external field was run through a Monte-Carlo simulation. The simulation was run using the 11.63 m, 3 MAG configuration. The results of this can be seen in Figure 19, where distinctive peaks

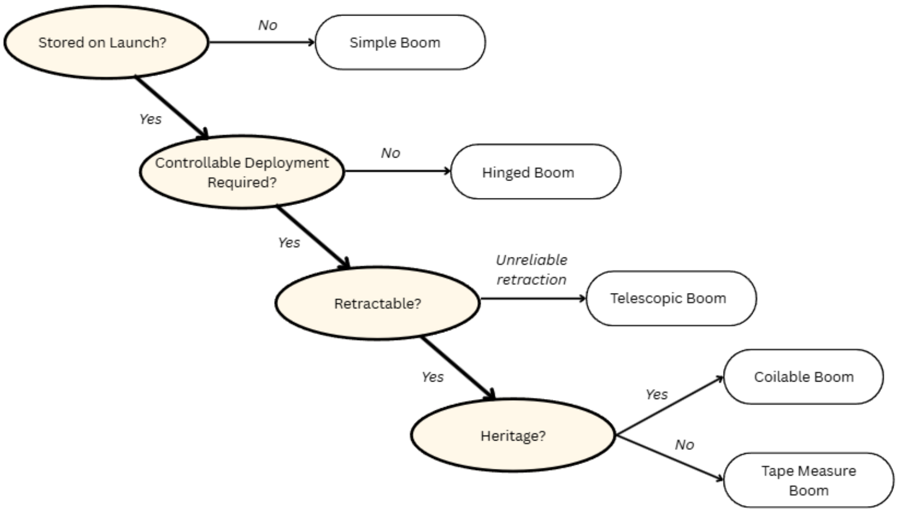

Figure 18: Boom Type Decision Matrix

that closely match those of Voyager 1 observations [60] can be seen. Although the present configuration does not resolve the change in field direction, a key signature of Heliopause exit, the results provide an initial validation of the model and indicate that DAYBREAK's MAGs should operate effectively at the Heliopause. If the contamination they received from DAYBREAK was too high, then the noise would dominate any detected external field, and the simulation would show a continuos flat line. As this is not seen, the calculation of a boom length that successfully keeps the MAGs away from DAYBREAK has proven effective.

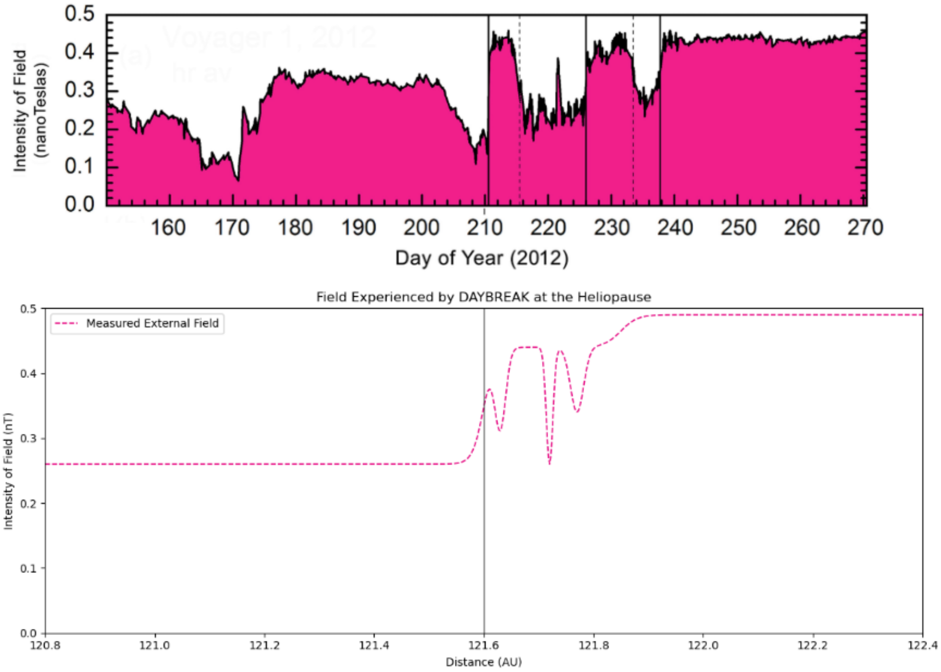

Figure 19: DAYBREAK Simulation vs Voyager 1 Data

10 Alternative Opportunities

10.1 Interplanetary and Interstellar Dust

DAYBREAK's journey to, and then through, the Heliopause presents exciting opportunities for novel science collection. In reference to 2, there remains an opportunity to map and model the distribution and density of interplanetary, and interstellar dust. This is an area of research that is actively being developed, with the Interstellar Dust Experiment (IDEX) currently undergoing calibration [61] before being mounted to the IMAP spacecraft [62]. This instrument aims to collect dust particles as it orbits Lagrange point 1, in order to determine the dusts elemental composition, speed, and mass distributions. This is accomplished by directing raw dust particles through a series of charged grids toward a gold-coated target plate. Upon impact, the dust grains are fragmented into their constituent ions, which are subsequently guided to a secondary detector for counting [62]. Owing to the intrinsically weak charge of these ions, amplification is required prior to detection. To achieve this, the ions are passed through specialised dynodes that enhance their charge, thereby rendering them measurable to the final detector [62].

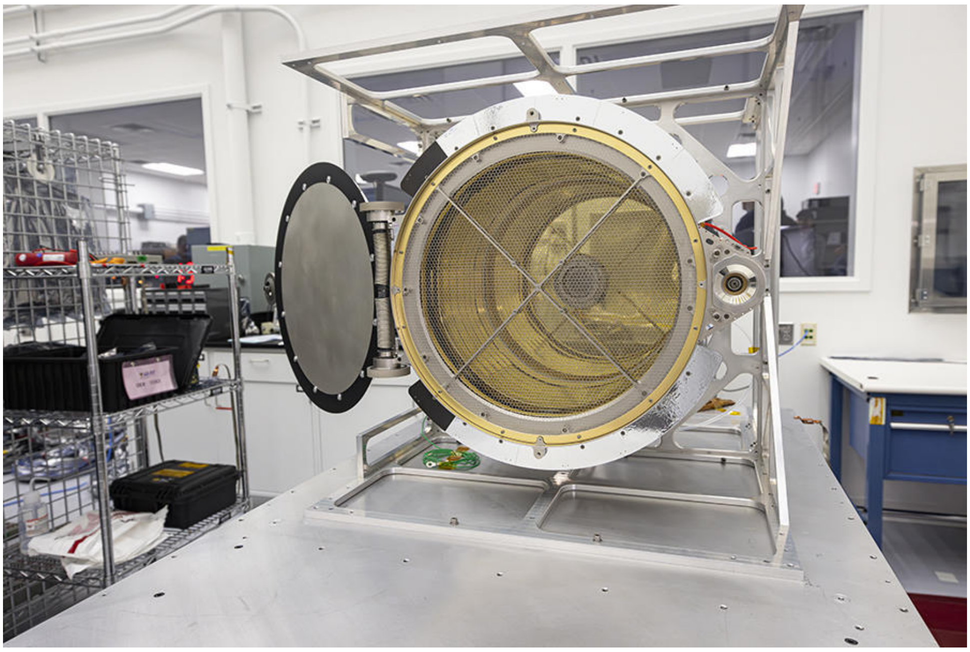

Figure 20: The Interstellar Dust Experiment

Image Credit: NASA/Johns Hopkins APL/Ed Whitman [63]

Its ability to self-clean by undergoing high temperature thermal cycles would ensure its continued use on a long-term mission such as DAYBREAK, by negating the build-up of dust residue [62]. However, the sheer size of the instrument proves problematic with DAYBREAK's limited structural size. Whilst no specific measurements are provided, the interactive model on the IDEX informational page shows a size of approximately 60 cm x 100 cm when fully open [62]. This is not practical for a small spacecraft such as DAYBREAK, and the power draw for the thermal cleaning process (not determinable through literature) is likely to be higher than DAYBREAK's power cycle will allow [2]. However, this particular aspect of the science goals could be achieved with a slight variation on the process of detecting dust. Rather than outright collection of particles, small, light, and low power draw ′patches′ could be used to detect the impacts caused by the spacecraft intercepting particulates along its trajectory. Not only has such an instrument already been developed, but it has flight heritage too. The Venetia Burney Student Dust Collector (SDC) flew aboard New Horizons, and is already uncovering areas of space presenting higher than modelled levels of flux [64]. Weighing just 1.6 kg and drawing only 5.1 W of power [65], the SDC comprises thin panels of PVDF, and is able to detect particles with masses as small as $m > 10^{-12}$ g [65].

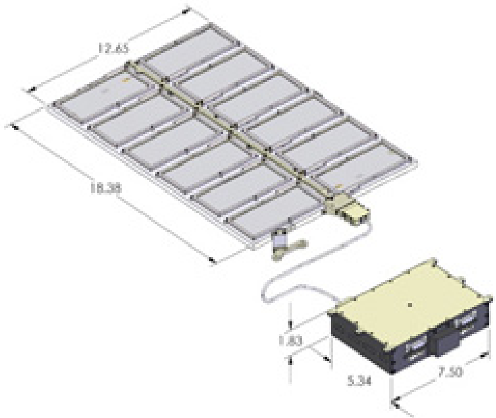

Figure 21: The Venetia Burney Student Dust Counter

Image Credit: Laboratory for Atmospheric and Space Physics [66]

It is the modular design of the PVDF sheets that is most attractive for use on DAYBREAK. Multiple groups of these detectors placed around the DAYBREAK structure will allow for multi-directional coverage, and by utilising multiple configurations (1 x 1, 2 x 2, 2 x 1 etc.) as applicable for individual space requirements, a DAYBREAK specific version of the SDC can be efficiently added on the spacecrafts ram surface. Concerns arise regarding the longevity however, as cumulative impacts could damaged the exposed plates, thus their ability to capture further data becomes compromised over the mission duration. Despite this concern, the SDC continues to functioning optimally at 60 AU [64].

10.2 Imaging

An early proposal for DAYBREAK explored the potential use of the spacecraft as a mobile imaging platform. The rationale for incorporating imaging capabilities into the mission framework was twofold. First, from a scientific standpoint, imagery could serve as a critical tool for planetary and small-body observations. During the Jupiter flyby, imaging would enable the collection of valuable data on atmospheric dynamics and satellite activity, thereby contributing to comparative studies of gas giants. Should mission trajectory allow [4], the spacecraft could also provide an unprecedented catalogue of observations of Uranus, supplementing and significantly extending the limited dataset obtained by Voyager 2 [67]. Moreover, any opportunistic encounters with Kuiper Belt objects along the flightpath would further enrich the limited dataset surrounding them, offering insights into their composition, morphology, and diversity. This would closely relate to, and expand upon, the discoveries of New Horizons [21]. Second, beyond the scientific objectives, imagery was viewed as a vital component for public engagement and mission visibility. High-resolution planetary and deep-space imagery has historically demonstrated a unique capacity to capture public imagination [68]. The dissemination of images from DAYBREAK would not only serve as a tangible representation of mission progress but also help to secure continued institutional and public support for the programme. Within this framework, Uranus emerged as the most strategically valuable target for imaging [4]. Scientifically, Uranus remains among the least well-characterised of the outer planets, and new observations would provide critical data for addressing longstanding questions regarding its atmospheric circulation [69], magnetic field asymmetry [70], and satellite system [71]. Publicly, the novelty of returning new images from a planetary system unseen for decades would likely galvanise significant attention, positioning Uranus imagery as both a cornerstone of the mission's research agenda and a key driver of public engagement.

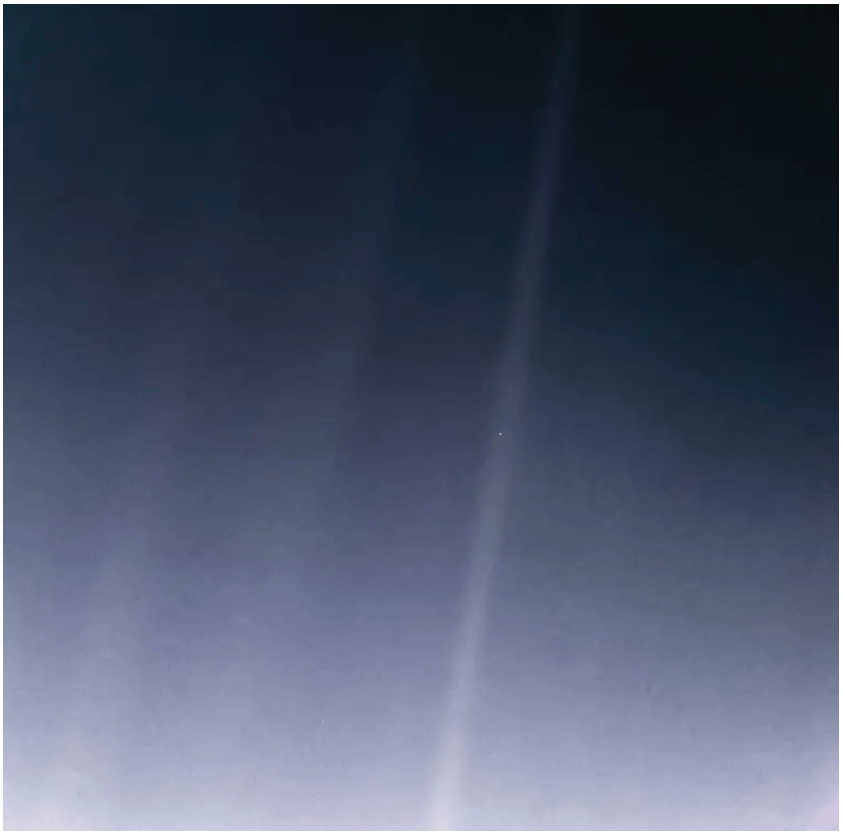

Figure 22: 'Pale Blue Dot' taken by Voyager 1, Feb. 14, 1990
Image Credit: NASA/JPL-Caltech [72]

Despite the initial enthusiasm surrounding the use of DAYBREAK as an imaging platform, significant technical and operational challenges were quickly identified. Chief among these were concerns regarding the longevity and sustained functionality of an imaging system over the course of the mission. Given the extended duration of DAYBREAK's mission, the reliability of optical systems posed a formidable obstacle. Prolonged exposure to radiation, thermal variations, and the cumulative effects of deep-space operations would likely degrade optical performance and mechanical components, raising doubts about whether an imaging payload could remain operational throughout the mission timeline. These concerns were judged to represent insurmountable risks relative to the mission's primary objectives. In addition to reliability issues, the inclusion of imaging instrumentation introduced considerable mass, power and data constraints. Whilst the flyby of Jupiter, and the potential flyby of Uranus occur early in the mission when maximum power is available [2], beyond this, the camera becomes essentially useless if no Kuiper Belt objects lie on the flightpath [4]. If, much in the way of Voyager, DAYBREAK's cameras are shut down [73], the subsystem becomes a passenger after just a few years of use [4], adding nothing but dead mass to the spacecraft. Realistically there will be no way of ejecting the system once it's purpose has been fulfilled, unless it can be determined that the safe deployment of explosive bolts can be used. Notably, such an ejection could actually provide a fractional increase in DAYBREAK's velocity through Newton's Third Law.

Taken together, these assessments led to the conclusion that, although scientifically and publicly appealing, an imaging platform aboard DAYBREAK would impose prohibitive risks and trade-offs. Consequently, the imaging concept was set aside in favour of mission architectures that prioritised robustness, efficiency, and alignment with the spacecraft's core investigative objectives.

10.3 Microlensing

With it's target of 200 AU, DAYBREAK actively seeks to operate at the furthest distance a spacecraft has ever planned to reach. But it is not limited to this particular distance, rather, 200 AU is just one point along the trajectory, and whilst it would signify the planned mission end for DAYBREAK, if the spacecraft still operates optimally, then there is no reason for a mission extension not to be granted and utilised.

Mission	Primary Mission (Years)	Total Mission (Years)	Extension (Years)	Extension Factor	Source
Pioneer 10	1.75	30.9	29.15	17.66	[74]
Pioneer 11	1.75	22.4	20.65	12.8	[75]
Voyager 1	5	48*	44	12	[76]
Voyager 2	5	48.1*	44.1	12.02	[76]
Galileo	8.14	13.9	5.75	1.71	[77]
Cassini	4	13	9	3.25	[78]
Juno	5	9.2*	4.2	1.84	[79]
New Horizons	10	19.7*	9.7	1.97	[80]

Table 11: Mission Duration and Extensions for Spacecraft at Jupiter or Beyond.
(*) Denotes an Active Mission

Using the data in Table 11, a median mission extension factor of 7.6x is typically seen in spacecraft operating beyond the orbit of Jupiter. If applied to DAYBREAK, a similar extension could see it operate for as long as 267 years, reaching a distance of 1546 AU. The potential longevity of the mission (assuming a perfect-case scenario) raises interesting possibilities, as at a distance of 550 AU, it becomes possible to use the Sun as a permanent gravitational lens [81]. Gravitational microlensing is a phenomenon that occurs when the gravitational field of a foreground object, typically a star, acts as a lens, magnifying the light from a more distant background source. This technique has proven particularly valuable for detecting faint or otherwise unobservable objects, such as exoplanets, as it does not rely on the intrinsic luminosity of the lensing body.

Theoretically, if DAYBREAK maintains the velocity it possesses at 200 AU (27.44695 km/s [4]), then 550 AU would be reached in 95 years from the date of launch. This time would be critical to enable future ground stations such as the ngVLA (which would have a theoretical link budget to as far out as 1020 AU [1]) to be built, and enable communications to be maintained with DAYBREAK at these extreme distances. Given the distances it hopes to achieve, DAYBREAK would be a perfect candidate to trial both this new observation technique, and ground station performance.

Despite the novel scientific potential, achieving a microlensing image was ultimately deemed impracticable for DAYBREAK. Primarily, to achieve a practical image size from a lensed background object (relative to the sun), a 12 metre radio antenna would be required [81]. This plays havoc with

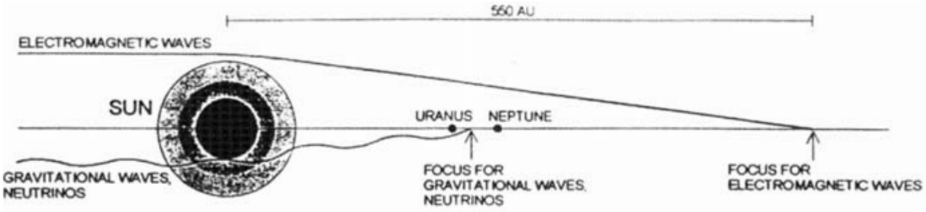

Figure 23: The Sun as a Lens

Image Credit: Dr. Claudio Maccone [81]

mass constraints on DAYBREAK, without even considering that the instrument would be effectively inactive for decades before reaching the required distance. Further, whilst it is likely that DAYBREAK will continue to operate beyond 200 AU, whether the degraded batteries, RTG's and electronics would still have the power to support a second, intensive mission phase, rather than a reduced and continually managed decrease in science operations (as seen with Voyager [22]), appears unlikely [2]. Further still, at these extended ranges, the background noise in communications with any ground stations increases, and there will become a point at which communication is no longer possible [1], even with the advanced capabilities of a station such as ngVLA. It was therefore determined that DAYBREAK would better off proving that missions can last extended lengths of time by continuing its primary observations, rather than being at the forefront of a lensing mission. Such a mission would require its own dedicated spacecraft, such as that proposed in the FOCAL mission [81].

11 Conclusion and Future Work

The instruments described and selected in this work outline the baseline standard from which DAYBREAK's final iteration instrument suite can be modelled in future studies. To reiterate the findings of this study, DAYBREAK's suite will possess a Magnetometer, a PWA, SWA, CRS, ENA Imager, and PUI Detector. These will be modelled off the heritage instruments of Europa Clipper, Cassini, MAVEN, Voyager, IMAGE, and JUNO respectively. By building upon the advancements from heritage missions, and updating them with modern materials, assembly techniques, and operating capability (through enhanced chips and circuitry), DAYBREAK is well placed to answer the objectives laid out in Section 2. All instruments are poised to shed light on multiple objectives, and often overlap in their function. As an example, the MAG, ENA Imager, and PWA, all work to map large scale structures, such as the Bow Shock and Heliopause, and by answering the same question from different angles, can work in harmony to build finely detailed models. Inevitably, new science questions will be generated as DAYBREAK extends along its trajectory, but the instruments selected, and with the parameters they were selected for, will provide the greatest opportunity to obtain this groundbreaking data.

The SWaP philosophy has driven the design of the payload, ultimately by constraining the number of instruments that can be taken. As explored in Section 10, there are different instruments that would be well placed to serve DAYBREAK for either raw data, public outreach, or both, but at present, there is no viable mass or power margin to include them (AD1). Future work can be done to manage these constraints, however. Using the Voyager CRS as an example, we can see in Figure 24 below, that the instrument comprises a large box, with aperture tubes on each corner. Fundamentally, this is a cumbersome design, and work to streamline the efficiency (perhaps through the combination of the apertures to reduce the size and weight) of this design would prove highly beneficial.

Trade off analysis performance varied wildly for each instrument, making conclusive analysis tricky. Instruments (such as the aforementioned CRS) simply lacked a sufficient amount of data for meaningful

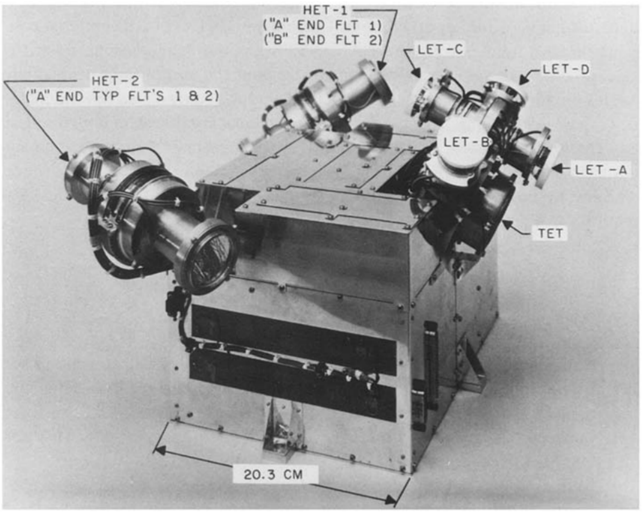

Figure 24: Voyager Cosmic Ray Experiment
Image Credit: E.C. Stone *et al.* [27]

conclusions to be drawn, whilst others consisted of intermittent values. Primarily, this stems from either a lack of published material due to missions being too new, or undigitised because they are too old. Another common issue was that material was not open access, or available through the University of Leicester, frustrating the efforts of obtaining relevant parameters. As a case for this, the modern IMAP system was identified too late in the research process to be included in the trade-off, but initial reading provided interesting applications for the SWA, and ENA imager. For example IMAP possesses three separate energy band imagers for its ENA objectives, allowing for incredibly high resolution details to be captured [82]. Further iterations of the study would include these within the trade-off.

One aspect of future work that DAYBREAK would benefit from is a more finely constrained magnetic model. Whilst the work within the scope of this study has provided a baseline value for boom length, the magnetic field has inherent uncertainties attached, as it does not include smaller magnetic sources such as electronics. By building up a more detailed model of the field, the error margin applied to the geometry can be reduced, and the length more accurately determined. The use of gradiometry can also be used to verify the calculated length, and was a process used by the Europa Clipper [50] to determine its own boom length. Structural analysis of the boom would prove beneficial, to determine whether the coiled structure would survive the dynamic conditions of launch. Further work will also need to establish the placement of instruments to achieve the best viewing angles for their apertures. At present, instruments have been placed on either side of DAYBREAK's octagonal shell, to allow for early investigation into spot shielding [3], but beyond this, no real investigation was conducted. Therefore at present, the layout is unoptimised, and would benefit from a full analysis of placement options. Overall however, a suitable payload that matches the science objectives of DAYBREAK has been selected, and provides an excellent baseline against which future iterations of the suite can be modelled.

To conclude, the author would like to sincerely thank the DAYBREAK UK and US based contingents, for their dedicated work ethic, camaraderie, and support. This study has benefited greatly from the guidance of Professor Nigel Bannister, Dr. Adrian Martindale, Dr. Emily Jane Watkinson, Professor Markus Rumpfkeil, and Dr. Rydge Mulford. The author hopes that this document is redeemable for a ticket to watch DAYBREAK launch. Elijah: Because of You. For You. *Thank You.*