

Serendipitous Spectral Characterizations of Asteroids with JWST

by

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Submitted to the Department of Earth, Atmospheric and Planetary Sciences
in Partial Fulfillment of the Requirements for the Degree of

Master of Science in Earth, Atmospheric and Planetary Sciences
at the Massachusetts Institute of Technology

September 2026

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ABSTRACT

Asteroids can enter the field of view while the James Webb Space Telescope (JWST) is observing unrelated targets, allowing their dispersed light to be recorded without dedicated observations. This study tested whether useful asteroid reflectance spectra could be extracted reliably from archival observations obtained with the Near Infrared Imager and Slitless Spectrograph (NIRISS). The Mikulski Archive for Space Telescopes (MAST) was searched for observations containing known asteroid positions. Candidate detections were confirmed, and one-dimensional spectra were extracted, calibrated, and compared with asteroid taxonomic templates. Spectra were recovered for 2008 TN215, 2012 QE2, 2015 FJ98, and one unidentified distant object. The spectra preserved continuum slopes and broad spectral shapes well enough to constrain each object to a small set of plausible classes. However, the limited wavelength coverage prevented reliable taxonomic classifications. These results demonstrate that serendipitous observations can provide meaningful first-order compositional information without requiring dedicated JWST observing time.

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Acknowledgments

I would like to thank my advisor, Professor Julien de Wit, for his guidance and support throughout this project.

I am also grateful to Artem Burdanov for working closely with me on the analysis and for his help with the spectral extraction, wavelength calibration, and interpretation of the results. Their feedback and support were essential to the completion of this thesis.

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Chapter 1

Introduction

1.1 Asteroids as Records of Solar System Evolution

Asteroids provide a record of the early stages of Solar System formation. Many are remnants of planetesimals, the small bodies that formed from solids in the protoplanetary disk and contributed to the growth of planets (Michel et al., 2015; Johansen et al., 2015). Although some asteroid parent bodies underwent substantial melting and differentiation, many asteroids preserve primitive Solar System material or records of intermediate stages of thermal processing (DeMeo et al., 2015; Michel et al., 2015; Weiss & Elkins-Tanton, 2013). Their present-day compositions, surfaces, and orbits also record later thermal, aqueous, collisional, and dynamical processing, making asteroid populations useful tracers of both formation conditions and subsequent Solar System evolution (Michel et al., 2015; Morbidelli et al., 2015).

The material incorporated into planetesimals depended on the physical and chemical conditions of the protoplanetary disk (Johansen et al., 2015; Morbidelli et al., 2015). Because disk temperature decreased with distance from the young Sun, different minerals, ices, and volatile-bearing materials could condense or remain stable at different heliocentric distances (Morbidelli et al., 2015; DeMeo et al., 2015). The water ice snow line is one example of such a boundary, separating regions where water ice could be incorporated efficiently into growing solids from warmer regions where it was less stable (Morbidelli et al., 2016). As planetesimals formed, they incorporated the solids available in their local disk environments (Johansen et al., 2015). Their compositions can therefore retain information about the temperature, volatile content, and chemical conditions of the regions where they accreted, although that record may later be modified by thermal alteration, aqueous processing, collisions, and dynamical evolution (DeMeo et al., 2015; Morbidelli et al., 2015).

Planetesimals experienced a continuum of thermal evolution rather than separating into exclusively primitive and fully differentiated bodies. Some remained unmelted, although they could still undergo thermal metamorphism, aqueous alteration, and chemical redistribution. With greater heating, metal-rich melts could migrate inward before extensive silicate melting, producing partially differentiated bodies with metal-rich interiors while preserving unmelted chondritic outer layers. More extensive melting could produce metallic cores together with igneous silicate mantles and crusts, although incomplete mixing and later collisions may have left these bodies compositionally heterogeneous rather than arranged in uniform layers (Weiss & Elkins-Tanton, 2013; Scheinberg et al., 2015). Because asteroid spectra primarily measure surface material, a primitive-looking surface does not necessarily rule out a partially or fully differentiated interior.

1.2 Asteroid Spectroscopy, Taxonomy, and Composition

Evidence for compositional diversity appears in the broad taxonomic structure of asteroid populations (DeMeo et al., 2009, 2015). Asteroids are commonly grouped into classes based on their spectral signatures (DeMeo et al., 2009). These classes are useful because many asteroids do not have spectra detailed enough for full mineralogical modeling, but their overall spectral shapes can still be compared across large surveys (DeMeo et al., 2009, 2015). The relative contributions of these taxonomic groups vary with both heliocentric distance and asteroid size. The inner main belt contains substantial S-complex and V-type material, but the balance changes strongly with size. C-complex asteroids account for only about 6% of the mass among inner-belt objects larger than 100 km, about 25% among objects between 20 and 100 km, and nearly as much mass as the S-complex among objects between 5 and 20 km (DeMeo et al., 2015). In the outer main belt, the C-complex contributes the largest fraction of the asteroid mass, while S-complex objects represent a smaller relative contribution (DeMeo et al., 2015). This compositional structure is shown in Figure 1.1, which places individual asteroid spectra in the broader context of Solar System formation and dynamical evolution. These classes provide a population-level framework for organizing asteroid surface diversity and for comparing individual objects with broader trends across the belt (DeMeo et al., 2015).

These taxonomic associations can also provide clues about material produced during planetesimal differentiation. C-complex surfaces are commonly associated with primitive carbonaceous material, while S-complex surfaces are dominated by olivine- and pyroxene-bearing silicates and are often linked to thermally metamorphosed chondritic material. More compositionally distinct classes may sample differentiated parent bodies: olivine-rich A-types may represent mantle-like material or partial-melting residues, V-types are associated with basaltic crustal material, and some M-types may contain metal-rich material derived from cores or other metal-enriched regions (DeMeo et al., 2015; Mahlke et al., 2022). These interpretations are not unique because taxonomy constrains surface composition rather than the complete internal structure of an asteroid.

Spectra are central to asteroid compositional studies because different surface materials absorb and reflect sunlight differently as a function of wavelength (Reddy et al., 2015; DeMeo et al., 2015). Reflectance spectra record these wavelength-dependent changes, allowing spectral slopes and absorption features to be compared across objects (DeMeo et al., 2009; Reddy et al., 2015). For instance, diagnostic features such as the $\sim 1 \mu\text{m}$ olivine band and the ~ 1 and $\sim 2 \mu\text{m}$ pyroxene bands can be used to constrain mafic mineralogy (Reddy et al., 2015). Since spectra primarily sample the surface rather than the full body, their interpretation can be affected by grain size, temperature, viewing geometry, and space-weathering processes (Reddy et al., 2015). For faint or serendipitously observed objects, recovered spectra are useful as compositional constraints rather than definitive mineralogical identifications (Reddy et al., 2015; DeMeo et al., 2015).

Large ground based surveys have demonstrated the value of near infrared spectroscopy for characterizing asteroid surfaces (Binzel et al., 2019). The MIT Hawaii Near Earth Object Spectroscopic Survey, or MITHNEOS, measured spectral properties for more than 1,000 near Earth objects and more than 350 Mars crossing asteroids (Binzel et al., 2019). Most of the near infrared observations were obtained with the SpeX instrument on NASA’s Infrared Telescope Facility (IRTF), which provided simultaneous wavelength coverage from approximately 0.8 to 2.5 μm . This range contains broad absorption bands near 1 and 2 μm that are commonly used to distinguish asteroid taxonomic classes and constrain silicate mineralogy (Binzel et al., 2019; Reddy et al., 2015).

Table 1.1: Major taxonomic complexes and related endmember classes in the classification of Mahlke et al. (2022). The listed properties describe broad spectral and compositional trends; individual objects within a class may remain compositionally diverse.

Broad grouping	Classes	General properties
C-complex	B, C, Ch, P	Generally dark and feature-poor, and broadly associated with carbonaceous and primitive material. Spectral slopes range from blue to red, and Ch-types show an absorption feature near $0.7\ \mu\text{m}$ associated with hydrated minerals.
C-complex endmembers	D, Z	Dark, largely featureless, and strongly to extremely red. These classes are separated from the main C-complex in spectral space but are connected to it through transitional P-type objects.
M-complex	K, L, M	Intermediate between the C- and S-complexes in spectral appearance and albedo, with generally weak or absent absorption features. The complex is highly compositionally diverse.
M-complex endmember	E	Characterized by very high albedo and commonly associated with enstatite-rich achondritic material.
S-complex	S, Q	Silicate-rich spectra with absorption features produced primarily by olivine and pyroxene. These classes are commonly associated with ordinary-chondrite-like material.
S-complex endmembers	A, O, R, V	More extreme silicate spectral shapes, including olivine-dominated A-types and basaltic, pyroxene-rich V-types.

Note. The X template is included in this work, but X-types are not a compositionally uniform group. In the taxonomy of Mahlke et al. (2022), objects formerly grouped in the X-complex are generally separated into the E, M, and P classes using spectral and albedo information.

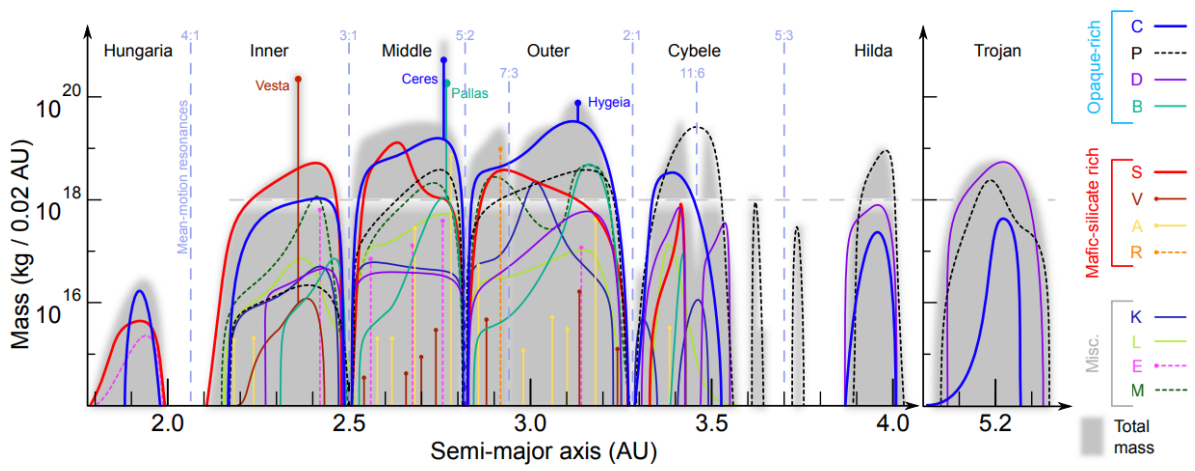


Figure 1.1: Compositional mass distribution throughout the asteroid belt and outer small-body populations. The gray background shows the total asteroid mass as a function of semi-major axis, while the colored curves show the mass contributions from different taxonomic classes. The figure illustrates that asteroid compositions vary with heliocentric distance: mafic-silicate-rich classes are more common in the inner belt, while primitive low-albedo and opaque-rich classes become more important farther from the Sun. Reproduced from DeMeo & Carry (2014).

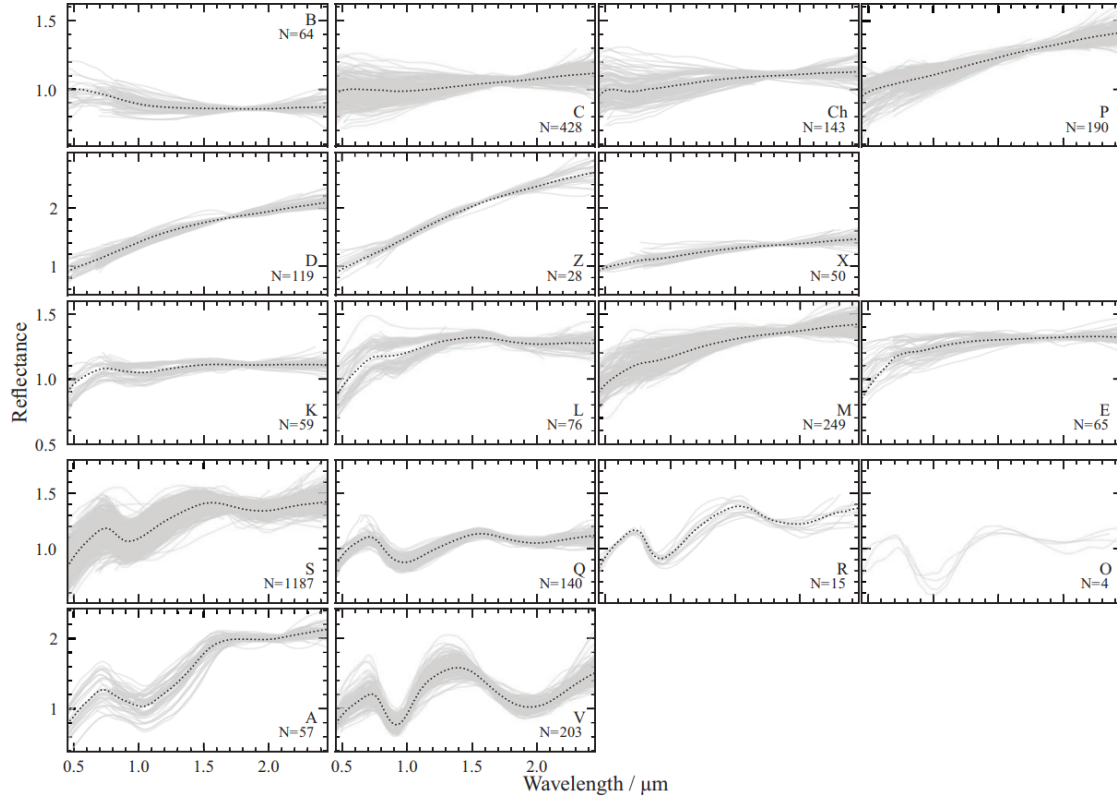


Figure 1.2: Representative reflectance spectra for the asteroid taxonomic classes used in this work. The different continuum slopes and absorption features show why visible and near-infrared spectra are useful for comparing asteroid surface properties and assigning broad taxonomic classes. Adapted from Mahlke et al. (2022).

1.3 Serendipitous Asteroid Observations with JWST

JWST has high-sensitivity infrared imaging and spectroscopic capabilities for Solar System observations, including observations of asteroids and other moving targets (Rivkin et al., 2016; Milam et al., 2016; Norwood et al., 2016). Ground based near infrared spectroscopy is complicated by absorption from Earth’s atmosphere, particularly strong water vapor bands near approximately 1.4 and 2.0 μm (Binzel et al., 2019). Space based observations avoid these telluric absorption bands and can provide more continuous spectral coverage across these regions, although instrumental calibration, source contamination, and background treatment remain important limitations (Rivkin et al., 2016; Milam et al., 2016; Norwood et al., 2016).

Although JWST supports dedicated Solar System observations, programs designed for other science goals can also record moving small bodies serendipitously when they cross the instrument field of view. This has been demonstrated in MIRI imaging. Müller et al. (2023) reported an unknown asteroid detected near the targeted asteroid (10920) 1998 BC1, and Burdanov et al. (2025) recovered numerous small main belt asteroids from MIRI exoplanet time series observations. These studies show that archival JWST data can contain scientifically useful small body detections. They motivate asking whether analogous serendipitous detections in JWST slitless spectroscopy can be used not only to identify moving sources, but also to recover usable one dimensional spectra.

1.4 Thesis Goals, Scope, and Organization

In this work, we investigate serendipitous small body detections in JWST data and assess whether reliable one dimensional spectra can be recovered for compositional analysis. We searched the JWST archive for serendipitously observed moving objects, with a primary focus on known asteroids, and identified promising detections in NIRISS wide field slitless spectroscopy observations. The final sample contains three known asteroids (2008 TN215, 2012 QE2, and 2015 FJ98) together with one unidentified slowly moving candidate. These sources were carried forward for spectral extraction and compositional analysis.

This thesis is organized as follows. Chapter 2 describes the archival search and candidate verification procedure. Chapter 3 presents the spectral extraction, wavelength calibration, instrument response correction, and conversion to reflectance. Chapter 4 presents the spectral results and compositional interpretation for each object. Chapter 5 discusses the reliability and limitations of the method, the value of archival NIRISS observations, and directions for future work. Chapter 6 summarizes the conclusions.

Chapter 2

Archival Search and Candidate Verification

2.1 Technical Background on NIRISS Wide Field Slitless Spectroscopy

2.1.1 NIRISS and Wide Field Slitless Spectroscopy

The Near Infrared Imager and Slitless Spectrograph, or NIRISS, is one of the instruments aboard JWST. In its wide field slitless spectroscopy mode, NIRISS records spectra for many sources across the detector at the same time. Unlike a conventional slit spectrograph, where light from a selected target enters through a narrow slit before being dispersed, slitless spectroscopy disperses light from every source in the field. This allows spectra to be obtained for many objects simultaneously, but it also means that nearby spectral traces can overlap or contaminate one another.

Each star, galaxy, or Solar System object in the field can therefore produce an elongated spectral trace rather than a single compact image. This makes wide field slitless spectroscopy useful for obtaining spectra of many sources simultaneously, including objects that were not the intended targets of the observation. However, because all sources are dispersed together, their spectral traces may overlap or contaminate one another. The wavelength range and detector orientation of these traces are controlled by the filter and grism used for the observation.

2.1.2 Filters and Grisms

NIRISS wide field slitless spectroscopy uses a filter and a grism together to control which wavelengths are recorded and how they are distributed across the detector. A filter transmits light within a selected wavelength range while blocking much of the light outside that range. Restricting the wavelength interval also shortens the resulting spectral trace, which reduces the chance that spectra from different sources will overlap.

A grism is an optical element that combines a diffraction grating and a prism. Both components separate light according to wavelength, allowing light of different wavelengths from the same source to fall at different positions on the detector. This produces an elongated spectral trace in which

position along the trace corresponds to wavelength. NIRISS wide field slitless spectroscopy uses two low resolution gratings, GR150C and GR150R. These gratings have similar spectral properties but disperse light in approximately perpendicular detector directions. GR150C produces traces that are approximately horizontal, while GR150R produces traces that are approximately vertical. The perpendicular dispersion directions of GR150C and GR150R can help distinguish overlapping spectra, because sources that overlap in one orientation may be separated in the other. The dispersion orientations of GR150C and GR150R are illustrated in Figure 2.1.

2.1.3 Spectral Traces and Detector Coordinates

In a slitless spectroscopic image, each source produces an elongated spectral trace rather than a single compact point. Light of different wavelengths falls at different positions along the trace, so position along its length contains spectral information. The trace also has a finite width because the image of the source is broadened by the telescope point spread function and the instrument optics.

Positions on the NIRISS detector are described using detector (x) and (y) pixel coordinates. These coordinates identify where the light falls on the detector, but they are not themselves wavelengths. The direction along which wavelength changes is called the dispersion direction. The perpendicular direction, across the width of the trace, is called the cross dispersion direction.

The relationship between the dispersion direction and detector (x) and (y) depends on the grism orientation and the position of the source in the field. Spectral traces may therefore appear approximately horizontal, vertical, or slightly slanted. To interpret an extracted spectrum physically, detector position along the trace must later be converted to wavelength using an instrument specific wavelength mapping. The wavelength calibration used for the moving objects in this work is described in Chapter 3.

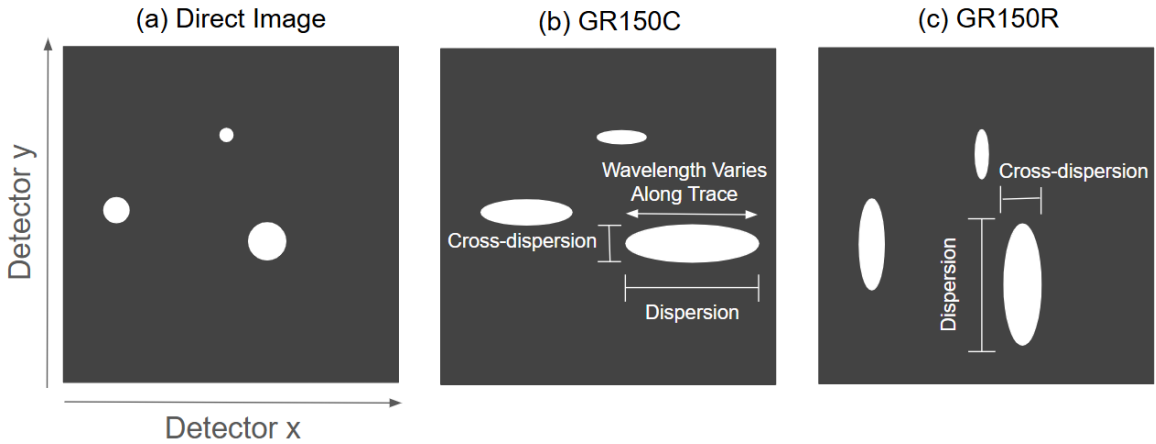


Figure 2.1: Conceptual illustration of NIRISS wide field slitless spectroscopy. (a) In a direct image, sources appear as compact objects at detector (x) and (y) positions. (b) The GR150C grism disperses light approximately along the detector (x) direction. (c) The GR150R grism disperses light approximately along the detector (y) direction. The long axis of each spectral trace is the dispersion direction, along which wavelength varies, while the perpendicular direction across the trace width is the cross dispersion direction. The detector axes shown in panel (a) apply to all three panels. The illustration is schematic and is not drawn to scale.

2.1.4 Opportunities and Challenges for Serendipitous Moving Objects

Moving Solar System objects behave differently from the distant stars and galaxies in a sequence of JWST integrations. Over the duration of an observation, background sources remain at nearly fixed detector positions, while an asteroid may shift measurably between integrations. This motion allows candidate asteroid spectra to be identified by blinking repeated images and checking whether a trace moves consistently relative to the surrounding field. Repeated integrations can also provide independent measurements of the same object, allowing the resulting spectra to be compared for consistency.

Difference imaging provides another way to isolate a moving spectrum. Subtracting one integration from another suppresses much of the fixed field while preserving the source at its two detector positions. The resulting difference image contains a positive trace at the object position in one integration and a negative trace at its position in the other. This can make a faint moving spectrum easier to identify and extract. However, if the object moves only a small distance, the positive and negative traces may overlap and partially cancel.

Serendipitous moving objects also present several challenges. Because every source in a slitless image produces a spectrum, an asteroid trace may overlap spectra from stars or galaxies, and different spectral orders may be difficult to distinguish. The moving source may also be faint or close to the detector edge. These objects were not the intended targets of the observations, so their positions, trace orientations, and contamination environments vary between datasets. Recovering their spectra therefore requires custom identification, extraction, and calibration procedures.

2.2 Candidate Generation Using MAST and the Small Body Identification Tool

To identify NIRISS observations that might contain serendipitously observed asteroids, we queried the Barbara A. Mikulski Archive for Space Telescopes using Python. For each observation, the MAST query provided metadata including the file name, observation time, field center coordinates, detector subarray, number of integrations, and observation duration.

The observation metadata were then supplied to the JPL Small Body Identification Tool to search for cataloged asteroids with known orbits that were predicted to lie within or near each NIRISS field at the observation time. The query used the field center, field dimensions, observation time, and JWST observer geometry to calculate the expected sky positions of known small bodies.

The search results were saved in a log that associated each predicted asteroid with a specific JWST file. For each entry, the log recorded the observation time, number of integrations, observation duration, asteroid name, predicted right ascension and declination, apparent visual magnitude, and angular distance from the field center. This log was used to determine which files should be opened in DS9 and where each asteroid was expected to lie relative to the NIRISS field.

The Small Body Identification results were treated as predictions rather than confirmed detections. A listed asteroid could fall outside the usable detector area, be too faint to detect, or be hidden by another dispersed source. Confirmation therefore required inspection of the NIRISS data and evidence of coherent motion across repeated integrations or files.

2.3 Organization of Candidate Files and Observing Modes

The candidate observations contained several different arrangements of files and integrations. Some objects appeared in multiple integrations within one `rateints` file. Other objects appeared in several separate files that each contained one integration. A smaller number were associated with only one file containing one integration.

Motion could be evaluated whenever repeated images were available. Therefore, a file containing only one integration was not automatically rejected if the same candidate appeared in additional files. In that case, the separate files could be blinked together. Candidates represented by only one usable image could not be confirmed from motion alone.

After the initial inspection, the observing modes were checked using FITS header metadata, including `EXP_TYPE`, `PUPIL`, and the instrument configuration. Wide Field Slitless Spectroscopy observations were identified by the WFSS exposure type and the GR150C or GR150R grism. Observations made in Single Object Slitless Spectroscopy mode used the GR700XD disperser and were designed around one primary target rather than a wide field of independent sources. These observations were excluded because the dominant target spectrum and its spectral orders made them unsuitable for the serendipitous field search performed here. NIRISS lamp exposures were also removed.

Only NIRISS WFSS observations were retained for the final candidate analysis. The retained observations used the GR150C and GR150R grisms together with the F115W, F150W, and F200W filters. These configurations produced traces with different detector orientations and wavelength coverage.

2.4 Visual Inspection and Blinking in DS9

The files identified through the archive search and Small Body Identification log were opened in DS9. Images were displayed using `zscale` or an equivalent contrast stretch to improve the visibility of faint dispersed traces.

When a file contained multiple integrations, the integrations were blinked in sequence. When a candidate appeared in several files containing one integration each, the separate files were blinked instead. GIFs were also produced from these sequences to allow the motion to be reviewed repeatedly.

The search focused on features that changed position while the surrounding stellar and galactic traces remained approximately fixed. Approximate detector coordinate boxes were recorded for possible moving traces and later used to locate the sources during more detailed inspection and extraction.

Additional features near a candidate were not automatically interpreted as separate moving objects. Slitless observations can contain more than one spectral order from the same source. A feature was treated as a separate candidate only when it showed its own coherent motion across the repeated images.

2.5 Position and Motion Based Verification of Known Asteroids

A known asteroid was considered securely identified when a coherent spectral trace appeared near the expected detector region and shifted consistently across repeated images. The surrounding dispersed field was required to remain approximately fixed relative to itself. This helped distinguish true source motion from detector artifacts, image scaling changes, and unrelated residual features.

Using these criteria, three known asteroids were confirmed: 2008 TN215, 2012 QE2, and 2015 FJ98. The traces of 2008 TN215 and 2012 QE2 could be followed across repeated integrations and files. Figure 2.2 shows the motion of 2012 QE2 across three successive integrations.

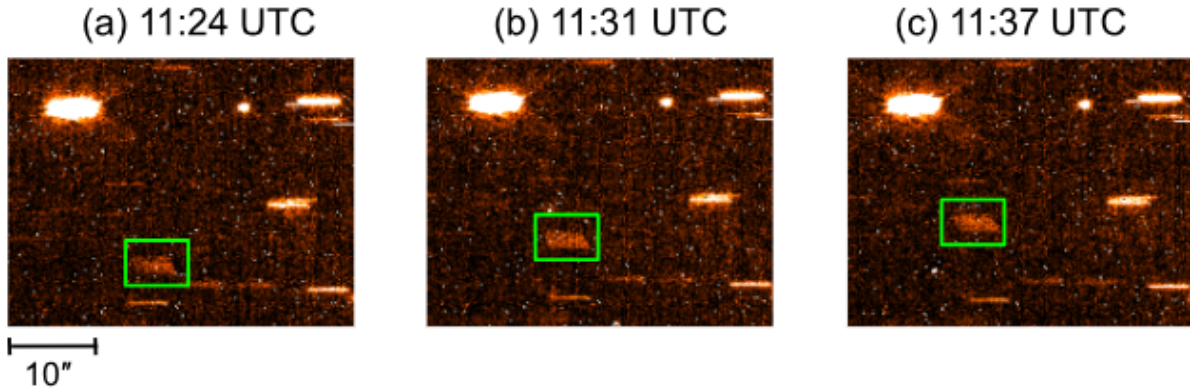


Figure 2.2: Example of motion based identification in the NIRISS WFSS data for asteroid 2012 QE2. Panels (a)–(c) show successive integrations obtained at 11:24, 11:31, and 11:37 UTC. The boxed spectral trace shifts between integrations, while the surrounding dispersed field remains approximately fixed, consistent with a moving Solar System object. A 10'' scale bar is shown in panel (a).

The identification of 2015 FJ98 required an additional positional check because the Small Body Identification results listed both 2015 FJ98 and 2004 MU2 for the same observing sequence. Their predicted sky positions were mapped onto the NIRISS detector, and the registration was checked using two field stars with known positions. This placed 2015 FJ98 near detector coordinates $(x, y) \approx (850, 2000)$, consistent with the moving trace near the top of the detector. The predicted location of 2004 MU2 was instead near $(x, y) \approx (812, 197)$, where no corresponding moving trace was detected. The upper moving spectrum was therefore identified as 2015 FJ98.

The three confirmed known asteroids were carried forward for spectral extraction.

2.6 Unidentified Slowly Moving Candidate

During inspection of the three integrations in the 2008 TN215 observation, a second faint moving source was noticed in the lower portion of the detector. The source was spatially separate from TN215 and moved coherently when the integrations were blinked. It was not listed in the Small Body Identification results for the observation and was therefore treated as an unidentified candidate.

The position of the candidate was measured independently in each integration using small image cutouts centered on the visually identified source. The measured detector centroids were approximately

$$(764.38, 933.07), \quad (759.24, 934.83), \quad (753.98, 935.18)$$

for integrations 0, 1, and 2, respectively. The displacement between two integrations was calculated as

$$\Delta r = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2}. \quad (2.1)$$

The same calculation was applied to 2008 TN215 using its measured detector positions in the same integrations. Angular displacements were estimated using a NIRISS pixel scale of approximately $0.065'' \text{ pixel}^{-1}$. The resulting detector and angular displacements for both sources are summarized in Table 2.1.

Table 2.1: Apparent detector motion of 2008 TN215 and the unidentified slowly moving candidate in `jw01571147001_06201_00001_nis_rateints.fits`.

Object	$\Delta r_{0 \rightarrow 1}$	$\Delta r_{1 \rightarrow 2}$	$\Delta r_{0 \rightarrow 2}$	Total angular motion
	pix	pix	pix	arcsec
2008 TN215	51.04	56.00	107.02	6.96
Unidentified candidate	5.43	5.27	10.61	0.69

Across integrations 0 to 2, the unidentified candidate moved by 10.61 pixels, compared with 107.02 pixels for 2008 TN215. TN215 therefore moved approximately 10.1 times farther across the detector during the same interval.

The much slower apparent motion is consistent with an object located farther away than 2008 TN215, which had a heliocentric distance of approximately 3.19 AU at the observation time. However, apparent angular motion also depends on orbital velocity, viewing geometry, the projected direction of motion, and the motion of the observer. The displacement ratio cannot therefore be converted directly into an accurate heliocentric distance.

Without reliable astrometry, an ephemeris match, or an orbit solution, the source cannot be securely classified as a trans-Neptunian or Kuiper Belt object. It is referred to throughout this work as an unidentified slowly moving candidate whose motion is consistent with a possible distant outer Solar System object.

2.7 Candidate Classifications and Non-detections

After the observing mode screening, the remaining WFSS candidates were classified according to whether a coherent moving trace could be identified. Predicted position, apparent magnitude, distance from the field center, and the availability of repeated images were considered together with the visual inspection results.

Candidates associated with SOSS or NIRISS lamp observations had already been removed and were

not counted as WFSS non-detections. Among the WFSS observations, candidates were retained when a trace could be followed coherently across integrations or files. Candidates were classified as non-detections when they were too faint, close to or beyond the adopted field boundary, represented by insufficient repeated data, or lacked a coherent moving trace.

The predicted positions of 2001 XF143 and 2014 JJ27 were beyond the adopted radial half width of the NIRISS field, and no corresponding traces were identified. Because the detector is square rather than circular, distance from the field center alone was not treated as definitive proof that a source fell outside the detector. The absence of a trace in the predicted region was also considered.

The asteroid 2025 PY12 was predicted within the field but had an apparent magnitude of approximately $V = 25.5$, making a reliable identification unlikely. Asteroid 2009 DU155 was predicted inside the field in several files, but no secure moving trace was identified.

Several additional checks involved candidates in or near the final observing fields. No moving trace was found at the predicted location of 2004 MU2 in the 2015 FJ98 observation. Candidate 2024 CQ12 was predicted near or beyond the adopted field boundary and was not securely detected. Asteroid 2015 OY156 was faint, with $V \approx 24.3$, and was located close to the detector edge. Asteroid 2007 EZ37 was predicted well within the field and was relatively bright, but no coherent moving trace was visible. Its non-detection may have resulted from spectral overlap, contamination, or insufficient contrast against the dispersed field.

Table 2.2 summarizes the principal WFSS candidates and their final classifications.

Table 2.2: Summary of the principal NIRISS WFSS candidates considered in this work and their final classifications.

Object	Status	Reason	Relevant information
2008 TN215	Included	Coherent moving trace across repeated images	Repeated detection
2012 QE2	Included	Coherent moving trace across repeated images	Repeated detection
2015 FJ98	Included	Moving trace matched the predicted detector position	Five integrations
Unidentified candidate	Included	Coherent slow motion in the TN215 field	Three integrations
2001 XF143	Non-detection	Predicted beyond the adopted radial field boundary; no coherent moving trace identified	$d_{\text{center}} = 69.7''\text{--}78.0''$
2014 JJ27	Non-detection	Predicted beyond the adopted radial field boundary; no coherent moving trace identified	$d_{\text{center}} = 79.2''\text{--}79.8''$
2025 PY12	Non-detection	Predicted in the field, but no coherent moving trace was identified; faintness likely limited detectability	$V = 25.5$
2009 DU155	Non-detection	Predicted in the field, but no secure moving trace was identified in repeated files	$V \approx 22.8$
2004 MU2	Non-detection	No coherent moving trace was identified at the predicted detector location	$(x, y) \approx (812, 197)$
2024 CQ12	Non-detection	Predicted near or beyond the adopted radial field boundary; no coherent moving trace identified	$d_{\text{center}} = 69.8''\text{--}73.2''$
2015 OY156	Non-detection	Faint and close to the detector edge; no coherent moving trace identified	$V \approx 24.3$
2007 EZ37	Non-detection	Predicted inside the field, but no coherent moving trace was identified	$V = 20.8$

2.8 Selection of the Final NIRISS WFSS Sample

The candidate generation, observing mode screening, visual inspection, and motion verification procedure produced a final sample of three known asteroids, 2008 TN215, 2012 QE2, and 2015 FJ98, together with one unidentified slowly moving candidate.

The available observations are summarized in Table 2.3. Both 2008 TN215 and 2012 QE2 were recorded in four separate files with three integrations in each file. The 2015 FJ98 observation contained five integrations in one file. The unidentified candidate was recorded in the first TN215 file and was followed across its three integrations.

Table 2.3: Final NIRISS WFSS sample. The listed duration is the approximate duration recorded for each file. The integration pairs used for spectral extraction are described in Chapter 3.

Object	Observation files	Configuration	Repeated data	Duration per file
2008 TN215	jw01571147001_06201, files 00001–00004	GR150R, F115W	4 files, 3 integrations each	39.19 min
2012 QE2	jw04681334001_06201, files 00001–00004	GR150C, F150W	4 files, 3 integrations each	19.86 min
2015 FJ98	jw04681166001_04201_00001	GR150C, F200W	1 file, 5 integrations	58.16 min
Unidentified candidate	jw01571147001_06201_00001	GR150R, F115W	1 file, 3 integrations	39.19 min

These four sources showed coherent motion in repeated WFSS data and had spectral traces that could be isolated for further analysis. They were therefore carried forward for spectral extraction. The construction of difference images, selection of integration pairs, extraction apertures, wavelength calibration, instrument response correction, and conversion to relative reflectance are described in Chapter 3.

Chapter 3

Spectral Extraction and Wavelength Calibration

3.1 NIRISS Data Products and Integration Structure

The spectral extraction used integration level JWST/NIRISS data products. An exposure is a complete observing sequence, while an integration is one independent detector measurement within that exposure. Retaining the individual integrations was necessary because the motion of each object between integrations was used to separate its spectrum from the approximately stationary background field.

For each integration, the analysis used the SCI, ERR, and DQ arrays. The SCI array contains the calibrated detector count rate in units of DN s^{-1} . The ERR array contains the corresponding pixel uncertainty in the same units, and the DQ array records pixel data quality conditions. The individual SCI arrays were used to construct difference images, while the ERR and DQ arrays were used during uncertainty propagation and unreliable pixel treatment.

3.2 Difference Image Construction and Pair Selection

For each moving source, a difference image was constructed by subtracting the SCI array of a reference integration from that of a target integration,

$$D = S_{\text{target}} - S_{\text{ref}}, \quad (3.1)$$

where S_{target} and S_{ref} are the SCI arrays from the target and reference integrations. Because stars, galaxies, and much of the detector structure remain nearly fixed, they are strongly reduced by the subtraction. The moving source remains as a positive spectral trace at its position in the target integration and a negative trace at its position in the reference integration.

The positive trace was used for spectral extraction. The negative trace was used to identify the reference position and to determine whether the two source occurrences overlapped. A difference was considered usable when the positive trace could be isolated without substantial overlap from the negative trace or from a nearby dispersed source.

Figure 3.1 shows an example difference image for 2012 QE2, including the positive extraction aperture and the negative reference trace.

All usable ordered integration differences were extracted. For 2012 QE2 and 2008 TN215, three integrations produced six ordered difference images. Both subtraction directions were retained for the final repeatability comparison. Products created by reversing the same integration pair were treated as consistency checks rather than independent observations.

For 2015 FJ98, the asteroid was inside the usable detector field in only two of the five integrations. The final products were $S_0 - S_1$, which compared the two source containing integrations, and $S_1 - S_4$, in which integration 4 provided a source free reference.

The unidentified slowly moving candidate shifted by only a small number of pixels between adjacent integrations. Differences involving integration 1 produced strong overlap between the positive and negative traces. Only the widest baseline products,

$$S_0 - S_2 \quad \text{and} \quad S_2 - S_0, \quad (3.2)$$

were therefore retained.

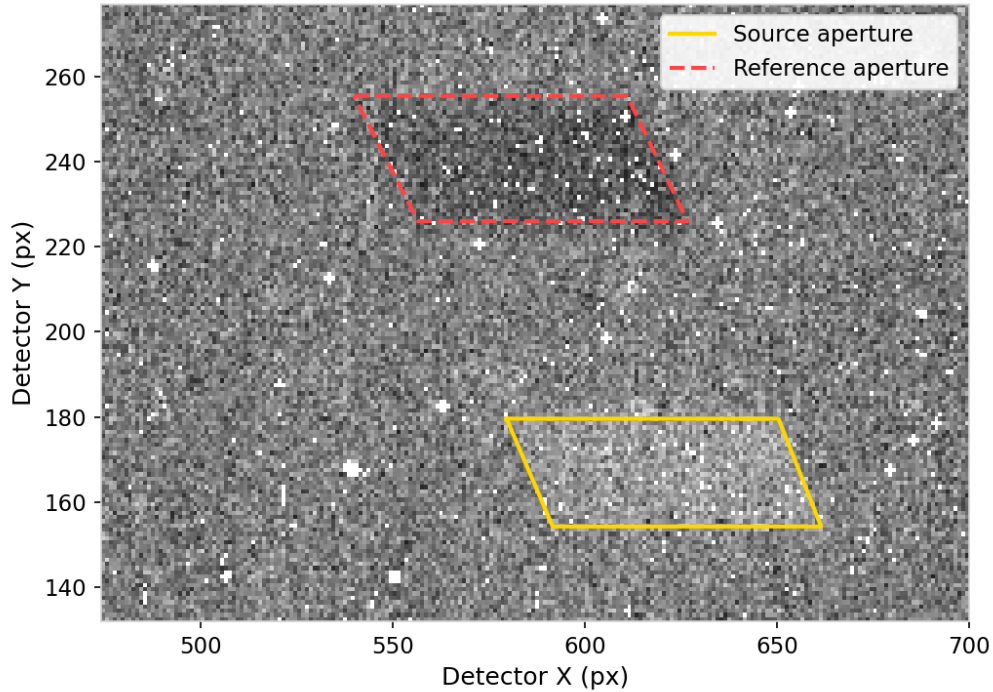


Figure 3.1: Example NIRISS difference image for 2012 QE2, constructed as $S_0 - S_2$. The moving asteroid appears as a positive spectral trace at its position in integration 0 and as a negative reference trace at its position in integration 2. The yellow aperture marks the positive trace used for spectral extraction, while the red dashed aperture marks the negative reference position. Stationary field sources are reduced by the integration subtraction.

3.3 Extraction Apertures and Spectral Binning

An extraction aperture was defined manually for each positive trace in the difference image. The aperture was chosen to follow the observed trace and to extend slightly beyond its visible edges so that the full source signal was included. Aperture coordinates were selected separately for each object because the trace position, orientation, and surrounding contamination varied between observations. The 2012 QE2 and 2015 FJ98 traces were extracted using slanted parallelogram apertures that followed their local dispersion directions. The nearly vertical 2008 TN215 and unidentified candidate traces were extracted using rectangular apertures. In each case, the aperture was divided into narrow bins along the dispersion direction, and the flux within each bin was summed across the cross dispersion direction.

Pixels intersected by an aperture boundary were assigned fractional weights. These weights were estimated using a 10×10 subpixel grid. The flux in one spectral bin was calculated as

$$F = \sum_{i \in A_{\text{src}}} w_i D_i, \quad (3.3)$$

where D_i is the difference image value in pixel i , w_i is the fraction of that pixel contained in the aperture, and A_{src} is the source region. The effective aperture area was

$$A_{\text{eff}} = \sum_i w_i. \quad (3.4)$$

A comparison between detector aligned bins and bins following the slanted trace showed that the overall spectral slopes were nearly unchanged. This indicated that the measured spectral shapes were not controlled by the precise bin geometry. Figure 3.2 illustrates the slanted aperture and the trace following bins used for 2012 QE2.

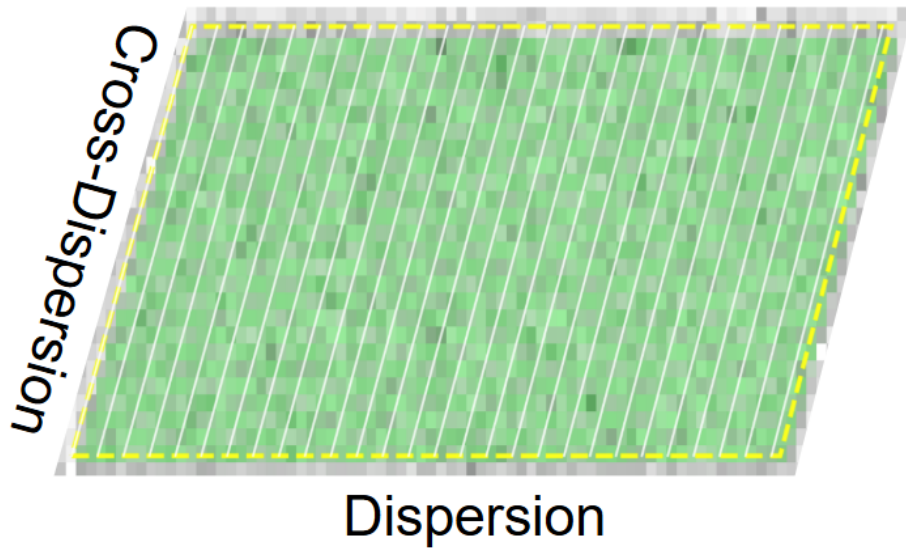


Figure 3.2: Example of the slanted extraction aperture and spectral binning used for 2012 QE2. The yellow dashed outline marks the full source aperture, and the white lines show the boundaries of successive spectral bins along the dispersion direction. Within each bin, the detector signal was summed across the cross dispersion direction to produce one point in the one dimensional spectrum.

3.4 Residual Baseline and Quality Checks

Difference imaging removed much of the stationary field, so the final science flux did not use a wavelength dependent local background subtraction. However, imperfect cancellation could leave a constant residual offset in the extracted spectrum.

The aperture was extended slightly beyond the source interval, allowing the signal immediately before and after the trace to be inspected. When the off source baseline was displaced from zero, one additive constant was applied to the full extracted spectrum so that the surrounding baseline was centered near zero. This corrected a residual zero level and did not alter the wavelength dependent spectral structure. For one FJ98 product, a constant 1.0 DN s^{-1} offset was removed before response correction and solar division. The residual zero level correction for the two final FJ98 spectra is shown in Figure 3.3.

Each difference image was also inspected for nearby traces, detector edge effects, and overlap between the positive and negative source positions. Difference products or wavelength regions with clear contamination were not used in the final interpretation.

Regions near the edges of the instrument response were treated cautiously. At low sensitivity, the response correction becomes large and can amplify both the measured signal and its uncertainty. Bins showing this behavior were trimmed before the final reflectance spectra were interpreted. For 2012 QE2, the two lowest wavelength bins were removed because they were strongly affected by the blue response edge.

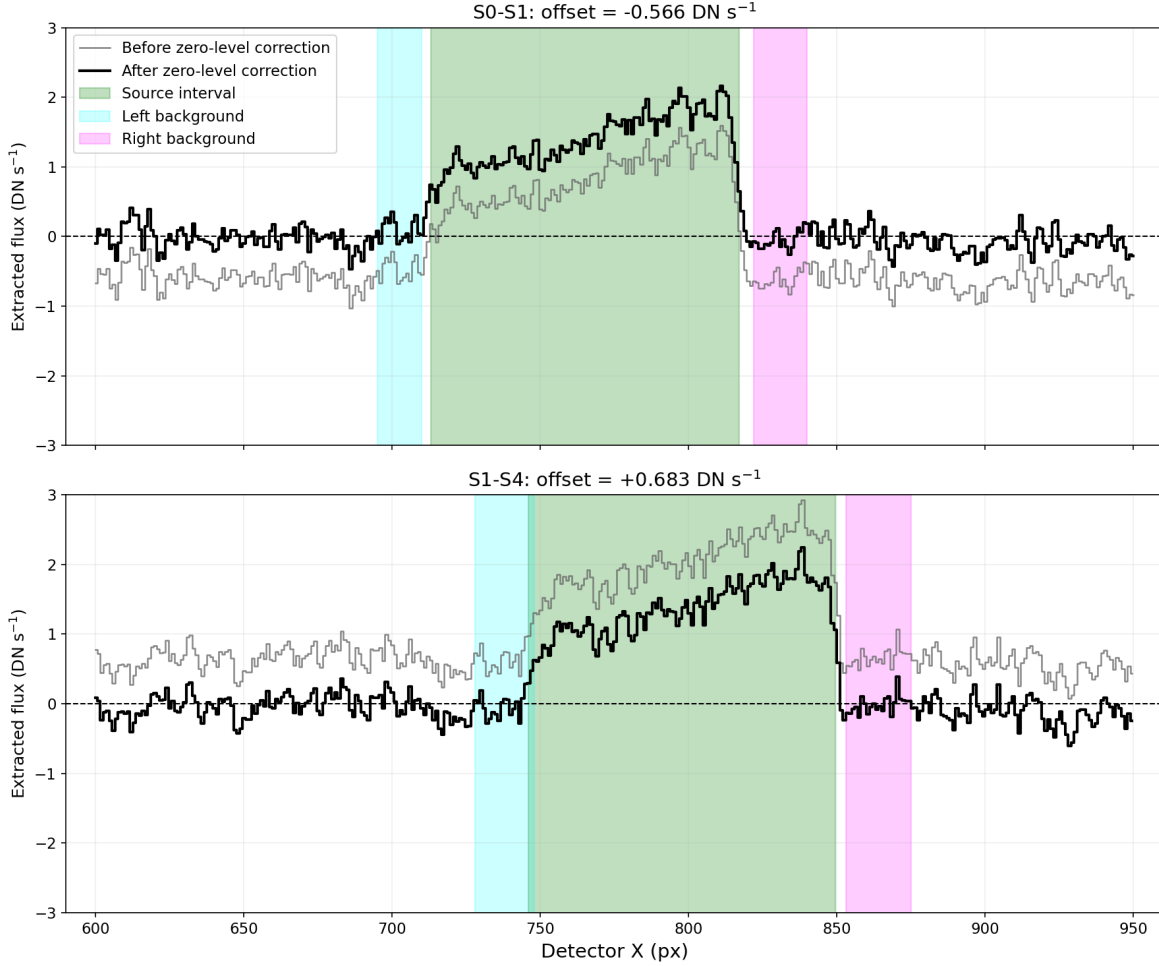


Figure 3.3: Residual zero level correction for the two final 2015 FJ98 difference spectra. The gray curves show the extracted flux before correction, and the yellow curves show the spectra after applying a single additive constant. The green regions mark the source intervals, while the cyan and magenta regions mark the off source intervals used to estimate the surrounding baseline. The correction centers the off source flux near zero without changing the wavelength dependent shape of the source spectrum.

3.5 Bad Pixels and Outlier Rejection

Unreliable pixels were identified using the JWST data quality arrays, checks for non-finite science or uncertainty values, and, for the vertical extraction products, a 5σ spatial outlier rejection within each spectral bin. Pixels carrying severe DQ flags such as `DO_NOT_USE`, `SATURATED`, `JUMP_DET`, `DEAD`, or `RC` were treated as bad.

Flagged pixels were repaired before the one-dimensional extraction rather than simply removed from the aperture sum. For each affected source or background bin, the bad science value was replaced by the median of valid donor pixels in the same local extraction bin. The corresponding uncertainty value was also replaced using the median variance of the valid donor pixels, with the local spatial scatter included where implemented. The repaired pixels were then carried through the same fractional-weight extraction as the other pixels.

Pipeline audit logs show that the repaired-pixel fraction was small. For 2015 FJ98, 82 source pixels out of approximately 1155 were repaired ($\sim 7.1\%$), with no source pixels removed by sigma clipping. Across the other extracted products, the typical repaired fraction was approximately 5 to 10% in the source and background apertures, while sigma-clipped source pixels were generally below 1%.

3.6 Uncertainty Propagation

Pixel uncertainties were propagated from the JWST ERR arrays. For a difference image, the variance in each pixel was calculated as the quadrature sum of the target and reference integration variances,

$$\sigma_{\text{diff},i}^2 = \sigma_{\text{target},i}^2 + \sigma_{\text{ref},i}^2. \quad (3.5)$$

The variance in one extracted spectral bin was then calculated using the same fractional pixel weights as the flux,

$$\sigma_F^2 = \sum_{i \in A_{\text{src}}} w_i^2 \sigma_{\text{diff},i}^2. \quad (3.6)$$

The reported 1σ error bars represent the propagated extraction uncertainty. They do not include uncertainty in the wavelength mapping, instrument response, solar model, normalization interval, or other systematic effects.

3.7 Detector to Wavelength Mapping Using Gaia Stars

3.7.1 Gaia Star Selection and Extraction

The asteroid observations were obtained in three different NIRISS fields and instrument configurations. The detector to wavelength mapping was therefore determined separately for each field using a Gaia star observed in the same field as the moving source. The calibration star and moving source were recorded with the same grism, filter, detector orientation, and optical configuration.

For each field, one primary Gaia star was selected for the final wavelength mapping. The primary calibration stars had effective temperatures available from Gaia DR3 and were used to select the

corresponding PHOENIX synthetic stellar models. Gaia 515 was used for the 2012 QE2 field, Gaia 3328 for the 2015 FJ98 field, and Gaia 0672 for the 2008 TN215 field.

Additional Gaia stars were inspected in some fields as secondary checks of the wavelength direction. In the 2015 FJ98 field, the secondary check also used a Gaia DR3 effective temperature. In the 2008 TN215 field, the secondary stars Gaia 5584 and Gaia 2864 used PHOENIX model temperatures estimated from Gaia BP–RP color. These secondary stars were used only to confirm the wavelength axis direction and were not used to define the final wavelength endpoints. Table 3.1 lists only the primary stars used for the final field specific mappings.

The unidentified slowly moving candidate appeared in the same GR150R/F115W observation as 2008 TN215 and therefore used the same Gaia 0672 wavelength calibration.

Table 3.1: Primary Gaia stars used for the field specific detector to wavelength calibration. All listed effective temperatures were obtained directly from the Gaia catalog.

Field	Gaia star	Gaia DR3 source ID	T_{eff} (K)	Configuration
2012 QE2	Gaia 515	792763414228385536	4263	GR150C/F150W
2015 FJ98	Gaia 3328	3836438034883443328	5823	GR150C/F200W
2008 TN215	Gaia 0672	6292803116492940672	4428	GR150R/F115W

3.7.2 Stellar Model Comparison and Wavelength Direction

Each extracted stellar spectrum was compared with a synthetic stellar model generated using the PHOENIX stellar grid through the `speclib` Python package. The model was interpolated onto the candidate wavelength grid and normalized over the same interval as the extracted spectrum.

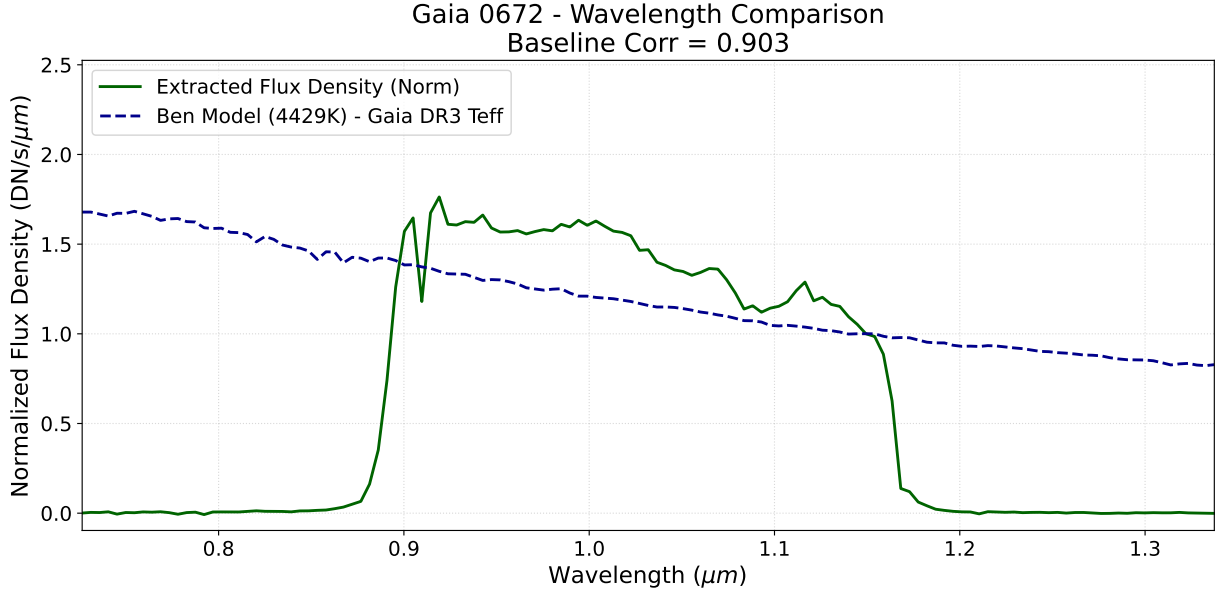
The detector position of a spectral trace does not by itself identify which end corresponds to shorter wavelengths and which end corresponds to longer wavelengths. Two possible wavelength assignments were therefore tested for each calibration star. In the first assignment, the shorter-wavelength model endpoint was placed at one end of the extracted detector trace and the longer-wavelength endpoint at the opposite end. In the second assignment, these endpoints were reversed.

For each assignment, a linear detector-to-wavelength relation was applied to the extracted stellar spectrum. The resulting spectrum was then compared with the PHOENIX model for that star over the reliable wavelength interval. The assignment that produced the closer continuum shape and stronger correlation with the stellar model was adopted. Figure 3.4 shows the stellar model comparisons for the selected wavelength directions in the three asteroid fields. For the primary Gaia 0672 comparison, the preferred direction produced a correlation of approximately 0.987. The secondary stellar comparisons gave correlations of approximately 0.94 and supported the same direction.

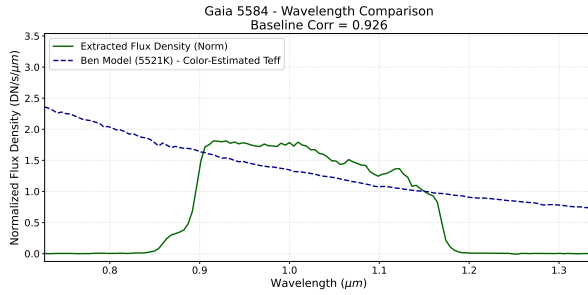
For the GR150C calibration, the preferred solution assigned longer wavelengths to lower detector x values and shorter wavelengths to higher detector x values.

3.7.3 Wavelength Endpoints and Linear Mapping

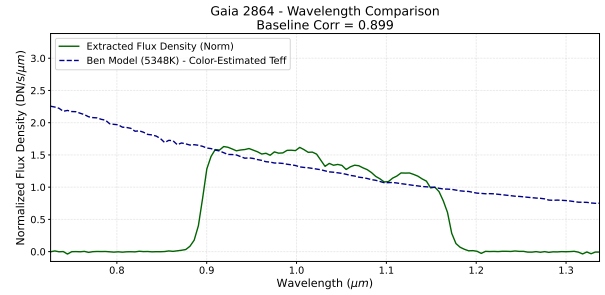
After the wavelength direction was established, the Gaia star spectrum was used to define two wavelength calibration anchors. The extracted stellar spectrum was examined as a function of



(a) Gaia 0672



(b) Gaia 5584



(c) Gaia 2864

Figure 3.4: Comparison of extracted Gaia star spectra with synthetic stellar models in the 2008 TN215 field. Panel (a) shows Gaia 0672, the primary star used for the final detector to wavelength mapping. Panels (b) and (c) show Gaia 5584 and Gaia 2864, which were used as secondary checks of the wavelength direction. All three comparisons supported the same orientation of the wavelength axis.

detector position. A robust peak flux, F_{peak} , was measured within the main spectral trace, while isolated noise spikes were ignored. The half power level was then defined as

$$F_{50} = 0.5F_{\text{peak}}. \quad (3.7)$$

The two positions where the flux crossed F_{50} on opposite sides of the trace were used as the detector endpoints. A crossing was accepted only when it represented a sustained transition between the off source baseline and the spectral signal, rather than a single noisy bin. Linear interpolation between the two neighboring bins was used to measure each crossing at subpixel precision,

$$p_{\text{cross}} = p_1 + \frac{F_{50} - F_1}{F_2 - F_1} (p_2 - p_1), \quad (3.8)$$

where p_1 and p_2 are the detector positions surrounding the crossing, and F_1 and F_2 are their corresponding flux values.

The same two half power locations were identified on the Gaia star spectrum in wavelength space. This provided two calibration anchors,

$$p_{\text{low}} \rightarrow \lambda_{\text{low}}, \quad p_{\text{high}} \rightarrow \lambda_{\text{high}}. \quad (3.9)$$

Which endpoint represented the shorter or longer wavelength was determined from the wavelength direction test described in Section 3.7.2. Figure 3.5 shows an example of the endpoint measurements in detector and wavelength space.

A linear relation was then used to assign wavelengths between the two anchors,

$$\lambda(p) = \lambda_{\text{low}} + \frac{\lambda_{\text{high}} - \lambda_{\text{low}}}{p_{\text{high}} - p_{\text{low}}} (p - p_{\text{low}}), \quad (3.10)$$

where p is position along the local dispersion direction. The half power positions served as calibration anchors and were not necessarily the first and last bins of the extraction aperture. A linear approximation was adopted because the analysis focused on broad spectral slopes and features over the limited wavelength range covered by each NIRISS trace.

3.7.4 Application to the Moving Object Spectra

For each extracted moving object spectrum, the measured low and high detector endpoints of the trace were assigned the corresponding wavelength endpoints from the calibration for that grism and filter configuration. A separate linear relation was then calculated for each source position and difference product.

For example, the FJ98 $S_0 - S_1$ spectrum used

$$\lambda(x) = 2.219028 - 0.004474 (x - 713.0), \quad (3.11)$$

while the $S_1 - S_4$ spectrum used

$$\lambda(x) = 2.219028 - 0.004510 (x - 746.002), \quad (3.12)$$

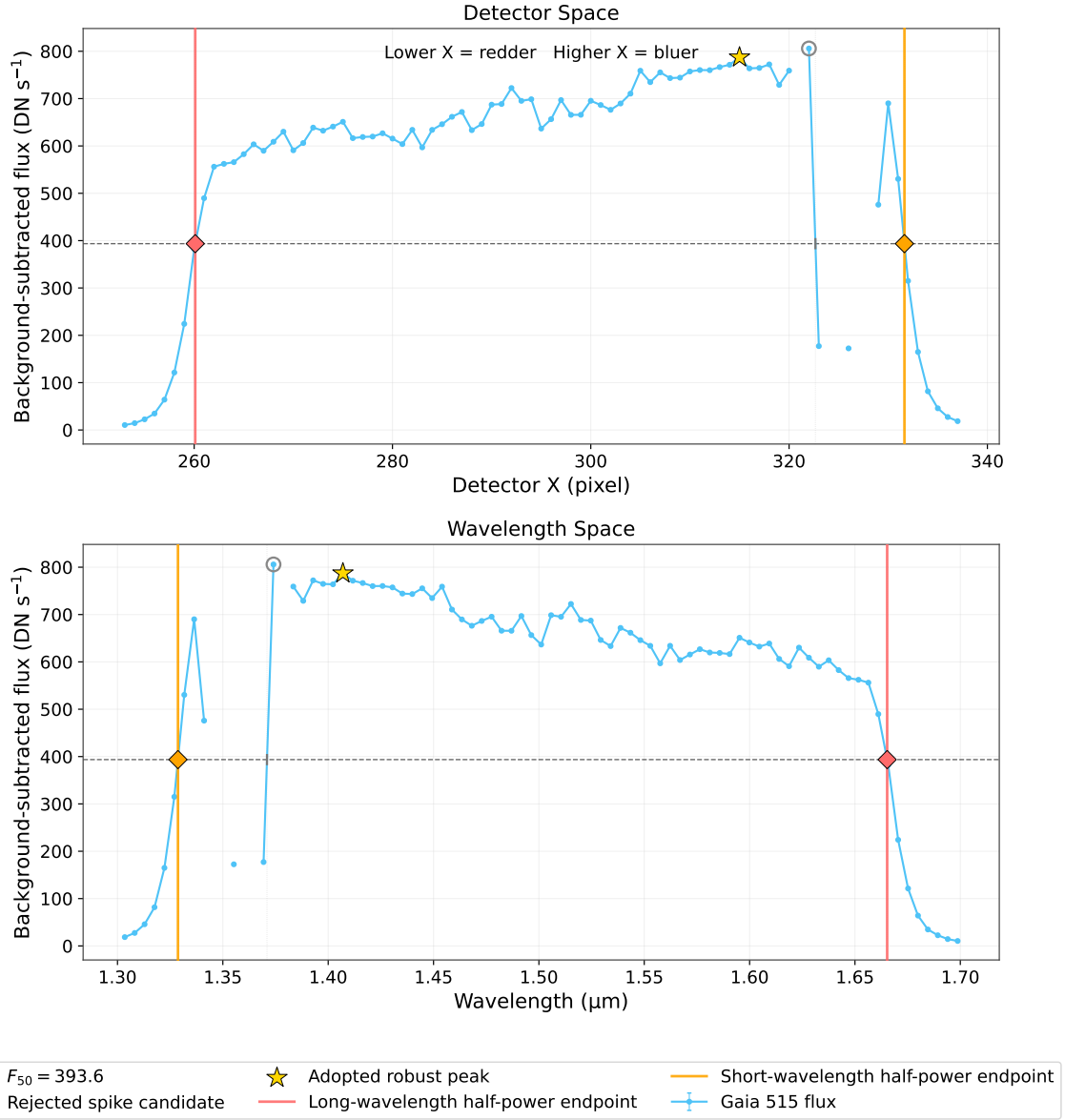


Figure 3.5: Half power endpoint calibration using Gaia 515 in the 2012 QE2 field. The extracted stellar spectrum is shown in detector space in the upper panel and wavelength space in the lower panel. The dashed horizontal line marks 50 percent of the adopted robust peak flux. The red and orange vertical lines mark the two sustained half power crossings. Matching these crossings in detector and wavelength space provides the wavelength anchors used for the linear detector to wavelength mapping. For this configuration, lower detector x corresponds to longer, redder wavelengths.

with wavelength in microns and detector position in pixels.

2012 QE2 used the calibration appropriate for GR150C/F150W. The 2008 TN215 and unidentified candidate spectra were obtained in the same GR150R/F115W exposure and used the same wavelength calibration, transferred to their separately measured detector trace endpoints.

When detector position increased in the direction of decreasing wavelength, the extracted arrays were reordered before plotting so that wavelength increased from left to right. The resulting wavelength solutions should be treated as approximate because they rely on measured trace endpoints, stellar model agreement, and a linear interpolation rather than a full object specific spectral WCS solution.

3.8 Instrument Response Correction

The sensitivity of NIRISS varies with wavelength, so a source with a constant spectral flux density would not produce a constant detector count rate across a spectral trace. This wavelength dependence was corrected using the **RELRESPONSE** array from the CRDS NIRISS **PHOTOM** reference file corresponding to each grism, filter, and spectral order.

The **RELRESPONSE** array represents the wavelength-dependent component of the photometric flux-conversion calibration and behaves as an inverse-sensitivity correction. Thus, although the physical instrument sensitivity can be viewed as being divided out, the stored CRDS correction factor is multiplied into the measured count-rate spectrum. The array was interpolated onto the wavelength grid of each extracted spectrum, after which the count rate and its uncertainty were corrected according to

$$F_{\text{corrected}}(\lambda) = F_{\text{measured}}(\lambda)R_{\text{photom}}(\lambda), \quad (3.13)$$

$$\sigma_{\text{corrected}}(\lambda) = \sigma_{\text{measured}}(\lambda)R_{\text{photom}}(\lambda). \quad (3.14)$$

Separate photometric-conversion curves were used for the three instrument configurations: GR150C/F150W for 2012 QE2, GR150C/F200W for 2015 FJ98, and GR150R/F115W for 2008 TN215 and the unidentified candidate.

3.9 Solar Spectrum Division and Reflectance Normalization

The response-corrected asteroid spectra were divided by a synthetic solar spectrum to remove the wavelength dependence of the incident sunlight. The solar spectrum was generated using the **speclib** Python package and the PHOENIX **newera_jwst** stellar model grid. The adopted solar-parameter model had

$$T_{\text{eff}} = 5778 \text{ K}, \quad \log g = 4.5, \quad [\text{Fe}/\text{H}] = 0.0.$$

A synthetic solar-parameter model was used rather than an observed solar spectrum because this correction requires only the relative solar spectral shape over the NIRISS wavelength interval, not an absolute solar irradiance calibration. The subsequent normalization removes the arbitrary

overall scale. The synthetic model also provides a continuous spectrum that can be evaluated and interpolated directly onto the wavelength grid of each extracted asteroid spectrum, without introducing additional sampling, calibration, or telluric artifacts from a particular observed solar reference spectrum.

The solar model was evaluated on a finely sampled wavelength grid and interpolated onto the wavelength grid of each asteroid spectrum. The solar-divided spectrum was calculated as

$$R_{\text{raw}}(\lambda) = \frac{F_{\text{corrected}}(\lambda)}{F_{\odot}(\lambda)}, \quad (3.15)$$

where $F_{\text{corrected}}$ is the response-corrected asteroid spectrum and $F_{\odot}$ is the interpolated solar model. The final relative reflectance spectrum was then normalized by the median value of R_{raw} over an object-specific reference wavelength interval,

$$R(\lambda) = \frac{R_{\text{raw}}(\lambda)}{\text{median}(R_{\text{raw}})_{\lambda_1 < \lambda < \lambda_2}}. \quad (3.16)$$

The extraction uncertainty was transformed using the same response and solar division factors as the measured spectrum. The resulting uncertainty does not include uncertainty in the response curve, solar model, wavelength mapping, normalization, or other systematic effects.

Each spectrum was normalized over a wavelength interval with stable response and no obvious filter-edge artifact. The 2012 QE2 spectra were normalized by their median between 1.50 and 1.60 μm . The 2015 FJ98 spectra were normalized between 1.95 and 2.05 μm . The 2008 TN215 and unidentified candidate spectra were normalized near 1.15 μm .

Bins near response-curve edges were removed when the correction strongly amplified the flux or uncertainty. The exact wavelength ranges retained for each object are reported with the final spectra in Chapter 4. Figure 3.6 shows the response-corrected spectrum, the interpolated solar model, and the resulting relative reflectance for one 2012 QE2 difference product.

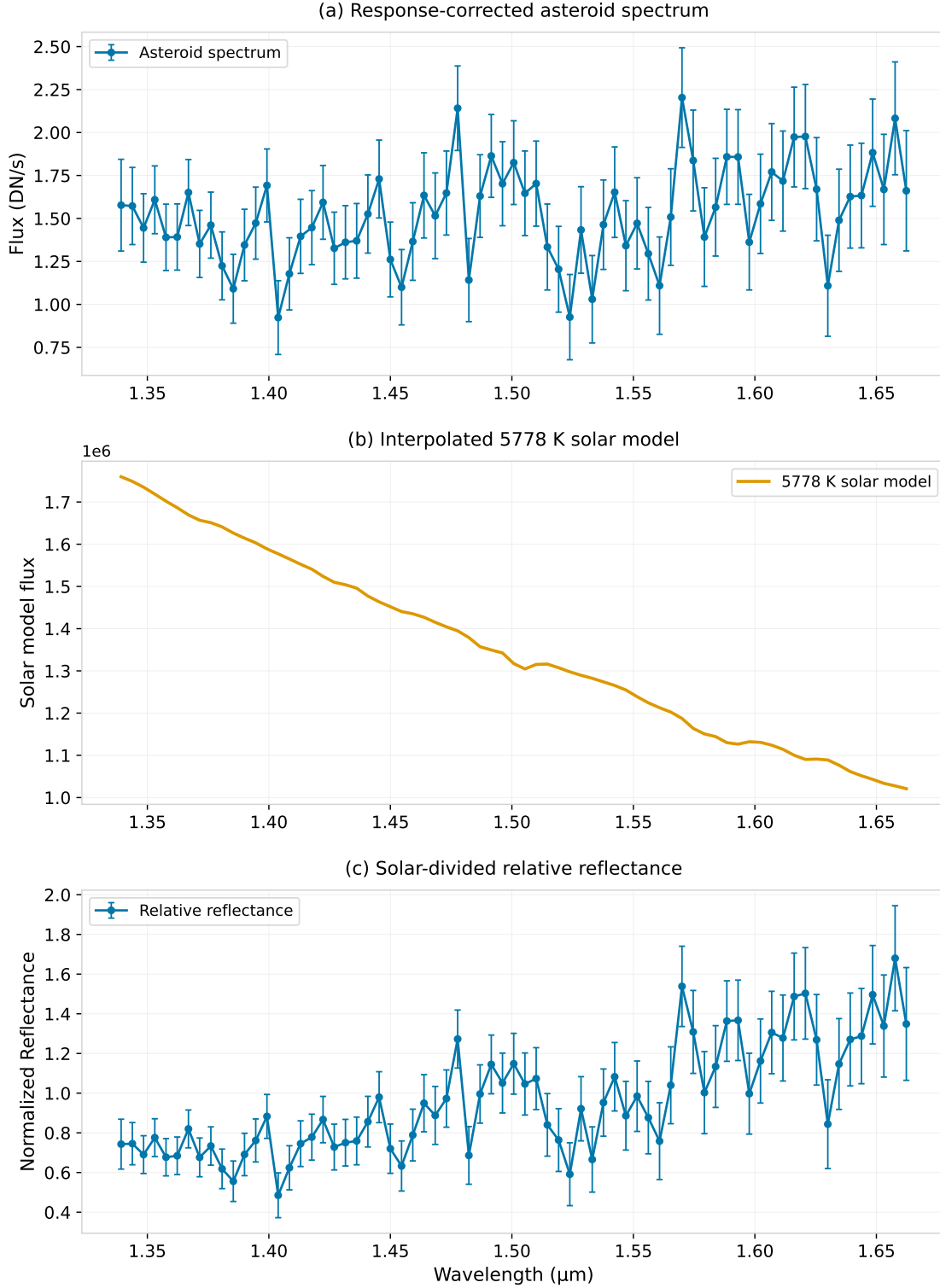


Figure 3.6: Example conversion from a response-corrected asteroid spectrum to relative reflectance for the 2012 QE2 $S_0 - S_2$ difference product. The upper panel shows the response-corrected asteroid spectrum, the middle panel shows the interpolated 5778 K synthetic solar-parameter model, and the lower panel shows the spectrum after division by the solar model. The final reflectance spectrum was subsequently normalized over the selected reference wavelength interval.

3.10 Combination of Repeated Spectra

After extraction, wavelength calibration, response correction, solar division, and normalization, the usable spectra from the different integration pairs were plotted for each object on the same panel. Pairs affected by strong overlap, contamination, or incomplete spectral coverage were excluded.

Where necessary, the retained spectra were interpolated onto a common wavelength grid covering the wavelength range shared by the usable products. At each wavelength, the median reflectance was calculated as

$$R_{\text{median}}(\lambda) = \text{median} [R_1(\lambda), R_2(\lambda), \dots, R_N(\lambda)], \quad (3.17)$$

where N is the number of usable integration pairs.

The standard deviation among the available spectra was also calculated separately at each wavelength,

$$\sigma_{\text{spectra}}(\lambda) = \text{std} [R_1(\lambda), R_2(\lambda), \dots, R_N(\lambda)]. \quad (3.18)$$

The combined spectrum was shown as the median together with $R_{\text{median}}(\lambda) \pm \sigma_{\text{spectra}}(\lambda)$. Because the standard deviation changes with wavelength, the upper and lower curves do not remain parallel to the median. A wider separation indicates wavelengths where the extracted spectra disagree more strongly.

Comparing the individual spectra helped distinguish repeatable broad spectral structure from features caused by residual background, detector position, or extraction noise.

A final median spectrum and wavelength dependent 1σ spread were therefore produced separately for each object. The six individual spectra and the resulting median for 2012 QE2 are shown in Figure 4.1. These four object specific median spectra were then plotted together on a shared wavelength axis, without vertical offsets, to compare their spectral shapes and wavelength coverage directly, as shown in Figure 3.8. Each object retained its own uncertainty envelope. No median was calculated across different objects. The median spectrum and its wavelength dependent spread were carried forward for the spectral slope measurements and taxonomic comparisons.

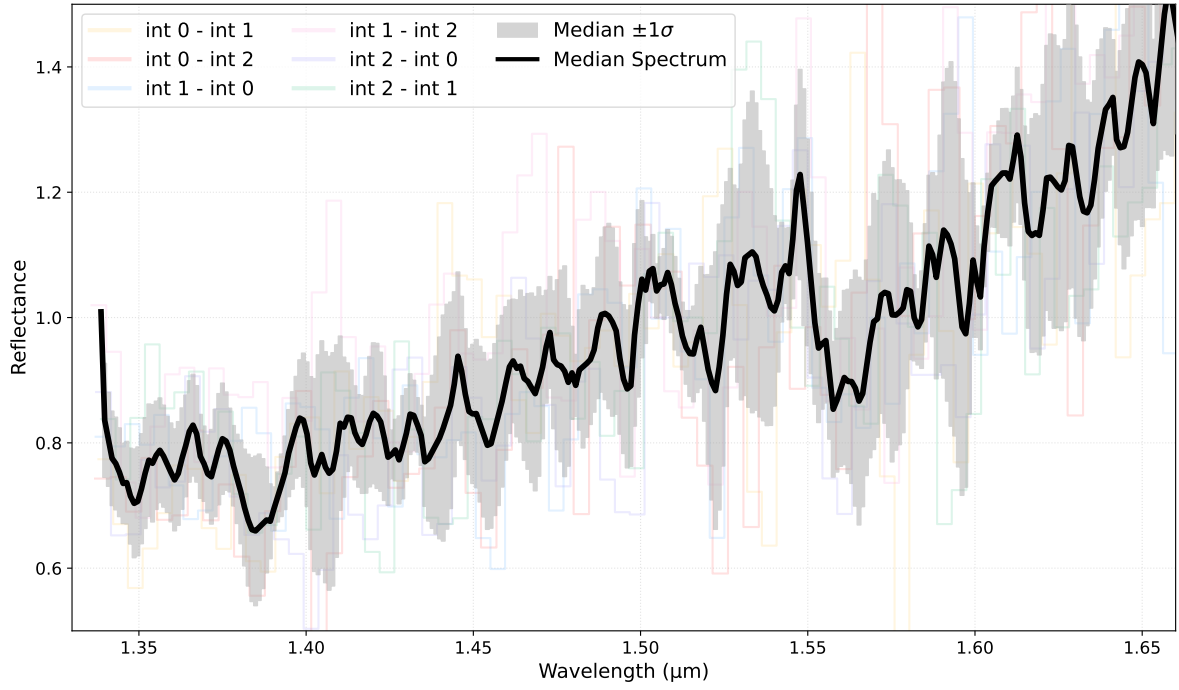


Figure 3.7: All six usable ordered difference spectra for 2012 QE2. The colored curves show the individual normalized reflectance spectra. The thick white curve shows the median reflectance at each wavelength, and the dashed white curves show the median plus and minus the wavelength dependent standard deviation among the six spectra.

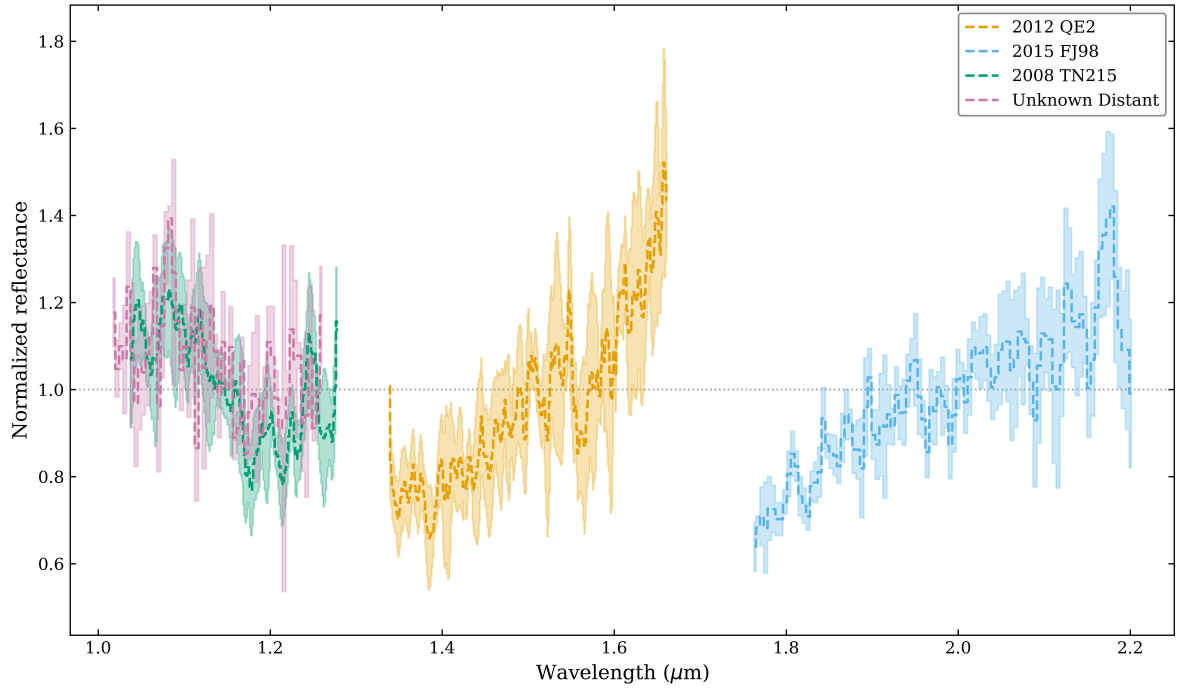


Figure 3.8: Comparison of the final median reflectance spectra for the four moving sources. Each curve shows the object specific median spectrum, while the shaded region shows the wavelength dependent standard deviation among its usable difference spectra. The spectra are plotted without vertical offsets to show their different spectral shapes and wavelength coverage.

Chapter 4

Results

4.1 Overview of the Recovered Spectra

Usable relative reflectance spectra were recovered for 2012 QE2, 2015 FJ98, 2008 TN215, and the unidentified slowly moving candidate. The following sections present the individual difference spectra, final median spectra, wavelength-dependent variation among repeated extractions, and reliable wavelength ranges for each source. Linear continuum slopes are reported for 2012 QE2 and 2015 FJ98, where a single linear trend provides a useful summary of the recovered spectrum. For 2008 TN215 and the unidentified slowly moving candidate, the interpretation focuses instead on broad spectral shape and the significance or repeatability of possible structure near $1.17\ \mu\text{m}$. Figure 3.8 provides an overall comparison of the four final spectra. Taxonomic and compositional interpretations are presented in Chapter 5.

4.2 2012 QE2

The recovered reflectance spectrum of 2012 QE2 is shown in Figure 4.1. The thick curve represents the median reflectance spectrum, while the wavelength dependent standard deviation shows the variation among the usable spectra. The dominant result is a broad increase in reflectance toward longer wavelengths.

The reliable wavelength range extended from approximately 1.34 to $1.66\ \mu\text{m}$. The two bluest spectral bins were excluded because they occurred near the sharp response edge of the F150W filter. In this region, the low instrument sensitivity caused the response correction to strongly amplify the measured flux and uncertainty, producing large and poorly repeatable values.

All six spectra showed a positive spectral slope, with reflectance increasing toward longer wavelengths. Over the interval from 1.35 to $1.65\ \mu\text{m}$, the slope measured from the final median spectrum was

$$m = 1.749 \pm 0.051\ \mu\text{m}^{-1}. \quad (4.1)$$

The linear fit had $R^2 = 0.81$, showing that a rising linear continuum described most of the broad spectral variation across the retained wavelength range.

The slopes of the six individual difference spectra ranged from $1.30 \pm 0.23\ \mu\text{m}^{-1}$ to $2.26 \pm 0.25\ \mu\text{m}^{-1}$.

Their mean slope was $1.81 \mu\text{m}^{-1}$, with a sample standard deviation of $0.32 \mu\text{m}^{-1}$. This range was consistent with the slope measured directly from the median spectrum and showed that the positive continuum slope was recovered across the different integration pairs.

The individual spectra showed greater disagreement at the level of individual wavelength bins. The wavelength dependent standard deviation was typically approximately 10 to 15 percent of the normalized reflectance, and the median absolute residual between pairs ranged from approximately 0.10 to 0.18. Small bumps and dips were not reproduced consistently among all six spectra. No distinct, repeatable broad absorption feature was therefore identified within the retained F150W wavelength range. The broad positive slope was more repeatable than the small scale spectral structure.

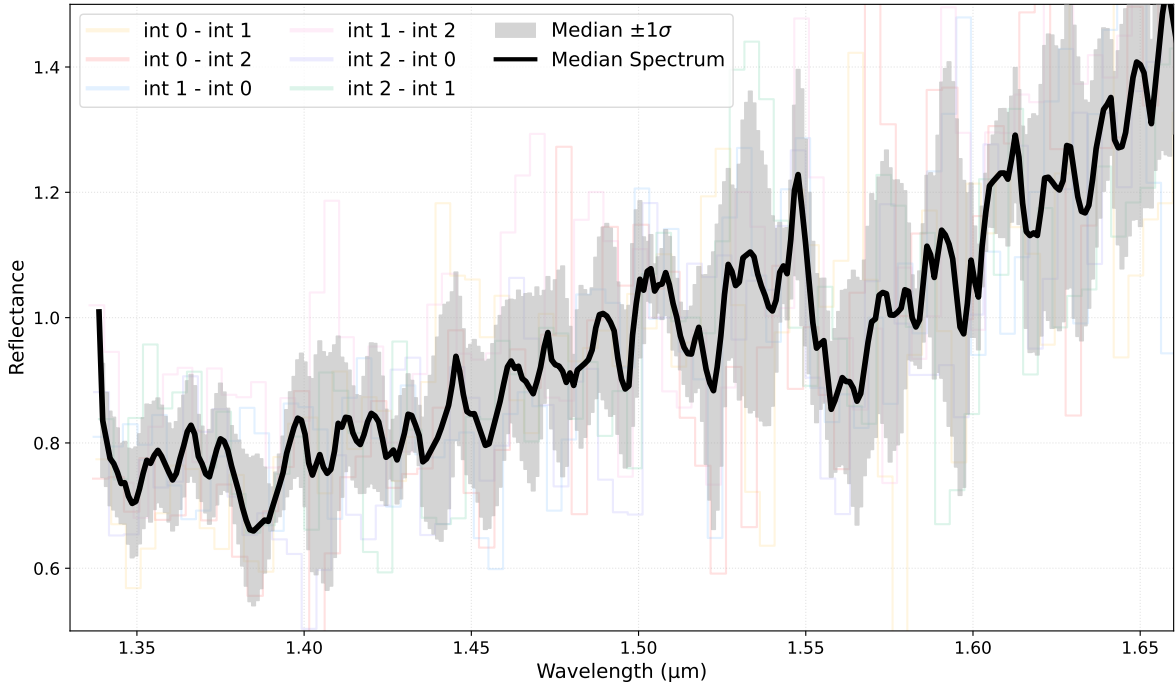


Figure 4.1: All six usable ordered difference spectra for 2012 QE2. The colored curves show the individual normalized reflectance spectra. The thick white curve shows the median reflectance at each wavelength, and the dashed white curves show the median plus and minus the wavelength dependent standard deviation among the six spectra.

4.3 2015 FJ98

The final reflectance spectra of 2015 FJ98, produced from the $S_0 - S_1$ and $S_1 - S_4$ difference images, are shown in Figure 4.2. Integrations 3, 4, and 5 were not used for target frames because the asteroid was only partly in frame for integration 3 and total out of frame for integrations 4 and 5. The shared reliable wavelength range extended from 1.7537 to $2.2146 \mu\text{m}$.

Both spectra showed a clear increase in reflectance toward longer wavelengths. A linear fit to the final median spectrum gave

$$m = 1.0818 \pm 0.0720 \mu\text{m}^{-1}. \quad (4.2)$$

The fit had $R^2 = 0.6888$, showing that a rising linear continuum described most of the broad variation across the measured wavelength range.

The continuum slopes were also consistent between the two retained products. The $S_0 - S_1$ spectrum had a slope of

$$1.1522 \pm 0.0886 \mu\text{m}^{-1},$$

while the $S_1 - S_4$ spectrum had a slope of

$$1.0113 \pm 0.0982 \mu\text{m}^{-1}.$$

These values agreed within their combined uncertainties and confirmed that the positive spectral slope was recovered in both difference products.

The two spectra had a Pearson correlation coefficient of $r = 0.6439$. Their median absolute difference was 0.0980 in normalized reflectance, corresponding to a typical fractional difference of approximately 9.07 percent. The median wavelength dependent standard deviation was 0.0490.

Although the broad rising continuum was repeatable, localized peaks and dips were not consistently reproduced between the two spectra. No clear, repeatable broad absorption feature was identified within the covered wavelength interval. The principal measured result for 2015 FJ98 was therefore a strong positive near infrared continuum slope.

Figure 4.2 shows the extracted reflectance spectra for 2015 FJ98 together with their median and wavelength dependent spread.

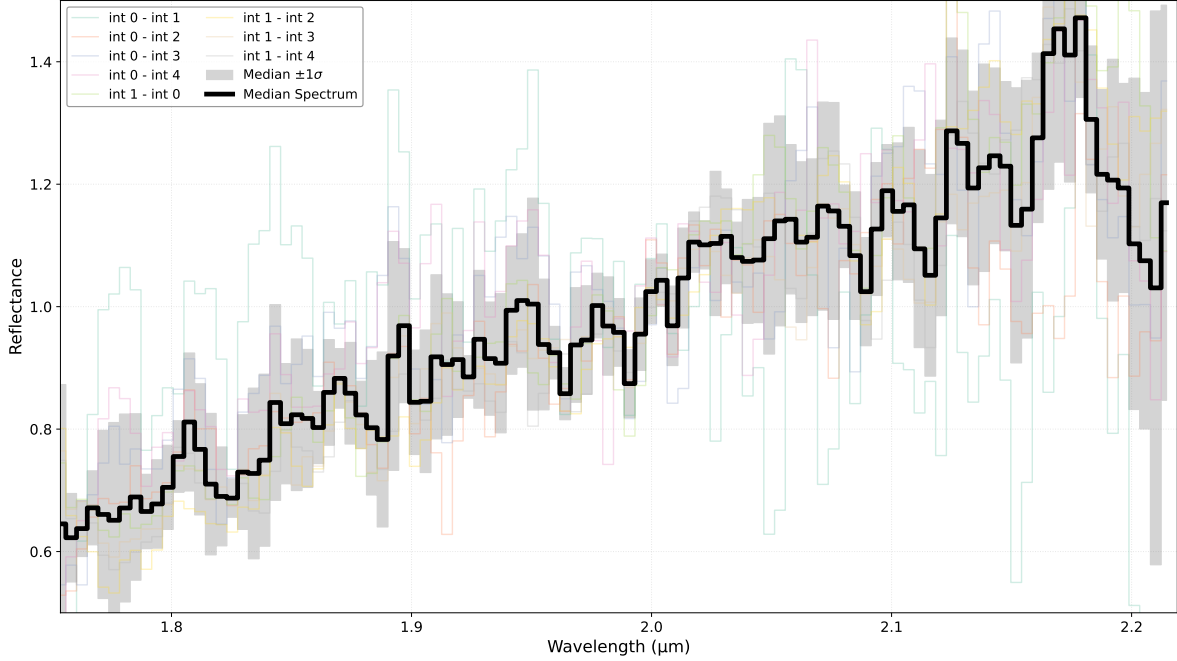


Figure 4.2: Extracted normalized reflectance spectra for 2015 FJ98. The colored curves show the individual ordered difference spectra. The thick white curve shows the median reflectance at each wavelength, and the dashed white curves show the median plus and minus the wavelength dependent standard deviation among the spectra.

4.4 2008 TN215

The recovered reflectance spectrum of 2008 TN215 is shown in Figure 4.3. The final usable wavelength range extended from 1.0163 to 1.2781 μm . The spectra were normalized using the median reflectance between 1.1392 and 1.1582 μm .

The 2008 TN215 spectrum was not well described by a single linear trend over the wavelength range. Instead, the median spectrum decreased from the short-wavelength edge toward a local minimum near 1.17 μm , then flattened and showed weak upward curvature toward the red edge. This behavior is reflected in the relatively low goodness of fit for a full-range linear model, which gave $R^2 = 0.428$. The spectrum was therefore interpreted mainly in terms of broad spectral shape rather than as a single measured continuum slope.

To evaluate whether the apparent depression near 1.17 μm was a statistically significant spectral feature, the reflectance in the 1.17 μm region was compared with nearby continuum windows using the propagated uncertainties. The resulting depression had a significance of approximately 2.1σ . A similar depression was present in all six ordered difference spectra, indicating that the structure is repeatable across the extracted products. However, because the significance remains below the usual 3σ threshold, the feature is treated as marginal rather than as a secure absorption band.

The median wavelength-dependent standard deviation among the six spectra was 0.104 in normalized reflectance. The typical propagated uncertainty in the combined spectrum was 0.068, corresponding to approximately 6.8 percent in normalized reflectance. The most robust result for 2008 TN215 is the non-linear broad spectral shape, including a marginal and repeatable depression near 1.17 μm ,

rather than a definitive diagnostic absorption feature.

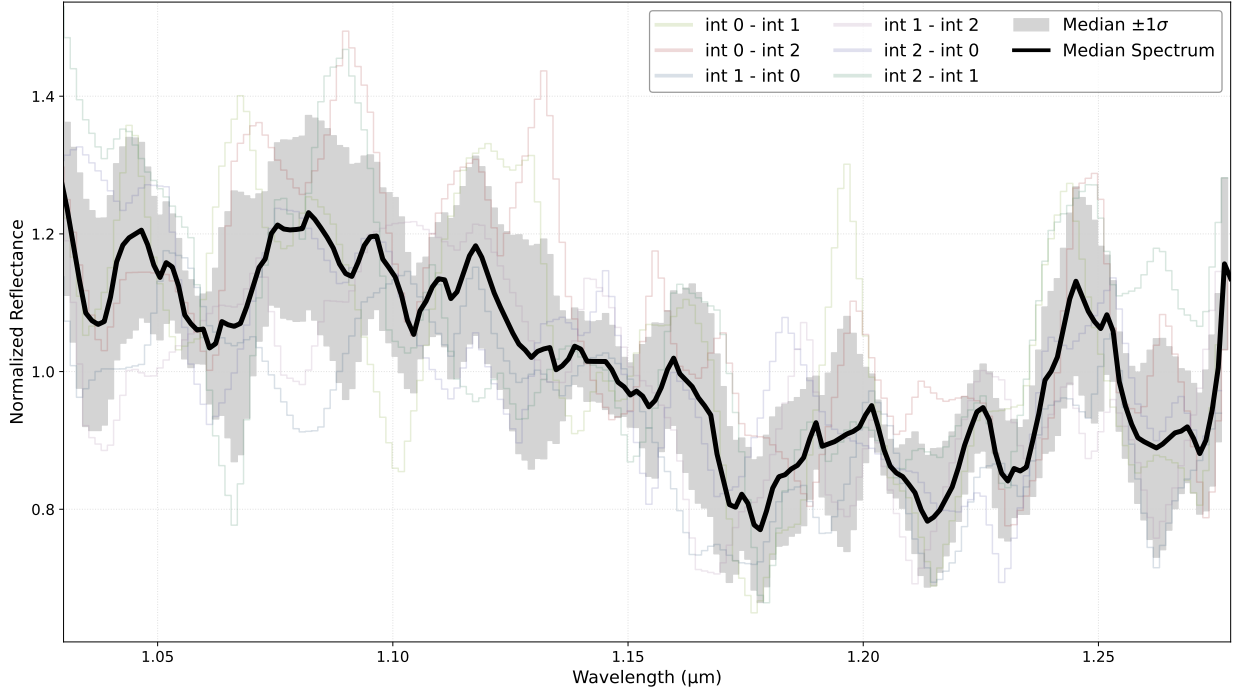


Figure 4.3: The six ordered difference spectra of 2008 TN215 after solar correction and normalization. The thick white curve shows the median spectrum, and the dashed white curves show the median plus and minus the wavelength dependent standard deviation. The low-wavelength filter edge has been excluded from the final usable range. The median spectrum shows broad non-linear structure, including a marginal depression near $1.17 \mu\text{m}$, but this feature does not reach the significance required for a secure absorption-band detection.

4.5 Unidentified Slowly Moving Candidate

The recovered reflectance spectrum of the unidentified slowly moving candidate is shown in Figure 4.4. The final reliable wavelength range extended from 1.0174 to $1.2776 \mu\text{m}$. The spectra were normalized around $1.15 \mu\text{m}$.

Only two ordered difference spectra were retained for this candidate, $S_0 - S_2$ and $S_2 - S_0$. Integration 1 was not include because in both difference pairs ($S_1 - S_0$ and $S_2 - S_1$), the target and reference aperture overlap. This is due to the slow motion of the object in the observation frame. Because these products were formed by reversing the same integration pair, they were treated as repeatability checks rather than as fully independent measurements. The spectrum was mostly flat over the wavelength range, with substantial bin-to-bin variation. For this reason, a linear slope was not used as the main diagnostic quantity for this source.

The overall shapes of the two spectra were broadly consistent. A comparison of their scaled shapes gave a reduced chi-squared value of 0.94 . A multiplicative factor of approximately 1.06 aligned the two unnormalized spectra, with a mean normalized residual of -0.025σ and a residual scatter of

approximately 1.38σ . This indicates that the two extractions recover a similar broad spectral shape, but not enough repeated information is available to interpret small-scale structure securely.

A window-based test was also used to check for a possible feature near $1.17\ \mu\text{m}$. The median reflectance in a $1.16\text{--}1.18\ \mu\text{m}$ window was compared with a local continuum interpolated between $1.10\text{--}1.13\ \mu\text{m}$ and $1.22\text{--}1.25\ \mu\text{m}$. The median spectrum showed an apparent drop of 0.16 ± 0.11 , corresponding to only 1.4σ . The two individual ordered spectra did not reproduce the feature consistently: the $S_2 - S_0$ product showed a marginal 2.6σ depression, while the $S_0 - S_2$ product showed no significant depression (0.4σ).

No statistically significant absorption or emission feature was reproduced at the same wavelength in both spectra. The apparent structure near $1.17\ \mu\text{m}$ is not treated as a diagnostic absorption feature. The most robust spectral result for the unidentified slowly moving candidate is that its recovered spectrum is weakly structured and approximately featureless within the uncertainties over the retained F115W wavelength range.

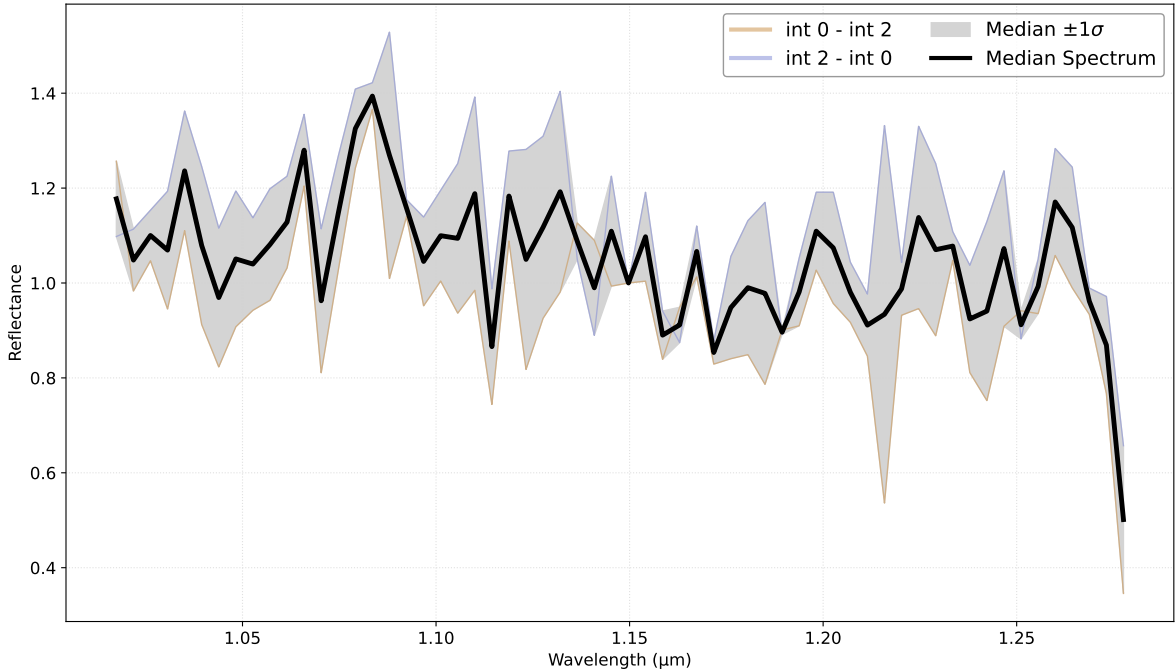


Figure 4.4: Normalized reflectance spectra of the unidentified slowly moving candidate. The colored curves show the $S_0 - S_2$ and $S_2 - S_0$ ordered difference spectra. The thick white curve shows the pointwise median spectrum, and the dashed white curves show the median plus and minus the wavelength-dependent spread between the two spectra. The recovered spectrum is weakly structured over the reliable wavelength range from 1.0174 to $1.2776\ \mu\text{m}$. No repeatable absorption feature is detected, including near $1.17\ \mu\text{m}$.

Chapter 5

Discussion

5.1 Interpretation of the Recovered Spectra

The spectra recovered in Chapter 4 show that serendipitous NIRISS/WFSS observations can provide useful relative reflectance measurements for moving Solar System objects. The strongest information in these spectra is the broad spectral shape, rather than narrow absorption features. Across the four sources, repeatable continuum behavior was recovered, but no object showed a secure absorption feature that was reproduced consistently across the available difference spectra.

The four sources did not show identical near-infrared behavior. 2012 QE2 showed a positive continuum slope across the F150W wavelength range, and 2015 FJ98 showed a strong positive continuum slope across the F200W wavelength range. In contrast, 2008 TN215 showed a more complex F115W spectral shape, with a broad decline toward a shallow local minimum near $1.17\ \mu\text{m}$ and weak curvature toward longer wavelengths. The unidentified slowly moving candidate was approximately flat over the F115W range, with small-scale bin-to-bin variations but no repeatable diagnostic absorption feature. Because the four spectra show different continuum behaviors, they are unlikely to be explained solely by one common instrumental shape imposed by the reduction process.

The most reliable spectral information is the broad behavior that was recovered in multiple extracted products. For 2012 QE2 and 2015 FJ98, the positive continua were seen in the retained spectra for each object. For 2008 TN215, the broad non-linear shape was repeatable, while the possible depression near $1.17\ \mu\text{m}$ remained marginal and below the usual threshold for a secure absorption-band detection. For the unidentified slowly moving candidate, there were too few usable products to confidently identify small-scale structure. This distinction is important because individual wavelength bins can be affected by residual background, imperfect field-source subtraction, detector noise, and response-correction uncertainties.

The absence of secure absorption features is also an important result. Because the filter-limited spectra do not fully sample both the 1 and $2\ \mu\text{m}$ regions commonly used for asteroid mineralogical interpretation, the interpretation is based mainly on continuum color and broad spectral shape rather than on absorption bands.

The recovered spectra should be treated as compositional constraints rather than complete mineralogical classifications. A red or blue continuum can suggest similarity to certain asteroid spectral classes, but continuum slope alone is not unique. Grain size, surface texture, space weathering, viewing geometry, and calibration systematics can all affect the measured spectral shape. Previous

asteroid surveys have shown that combining visible and near-infrared spectra provides stronger constraints on taxonomic class and mineralogy than either wavelength region alone (Binzel et al., 2019). In this work, the filter-limited NIRISS spectra provide partial taxonomic context, not complete visible-to-near-infrared classifications.

5.2 Taxonomic Template Comparisons

To place the recovered spectra in context, each final median spectrum was compared with the 17 asteroid taxonomic representative spectra of [Mahlke et al. \(2022\)](#). The comparison used only the wavelength interval covered by each NIRISS spectrum. For each object, the asteroid spectrum and every template were independently median-normalized using the same object-specific normalization interval adopted for the final reflectance spectrum. No fitted multiplicative scaling, additive offset, spectral-slope correction, wavelength shift, smoothing, or template reshaping was applied. The vertical offsets in [Figure 5.1](#) are used only to separate the curves visually and were not part of the quantitative comparison.

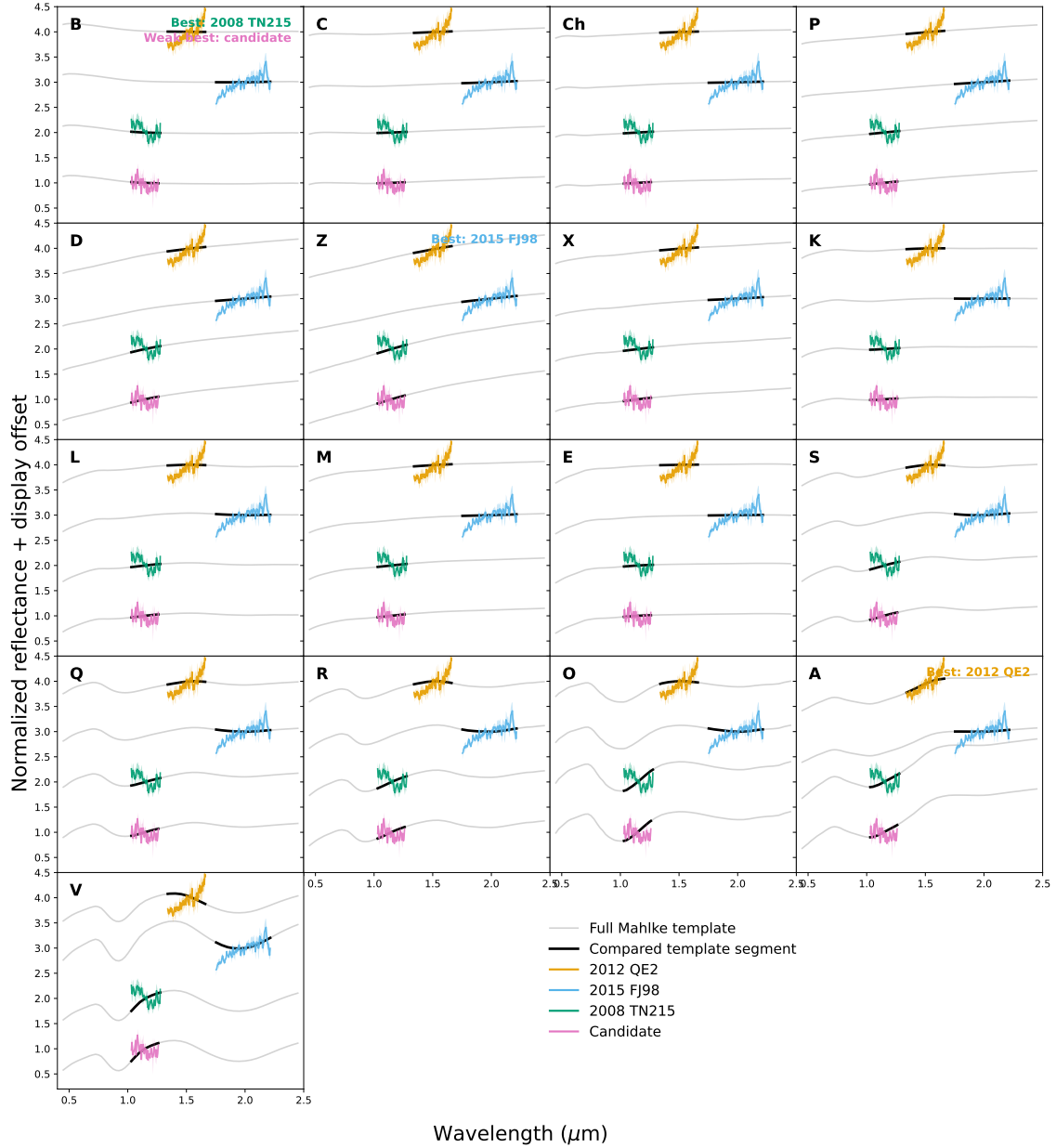


Figure 5.1: Comparison of the four recovered reflectance spectra with the 17 taxonomic representative spectra of Mahlke et al. (2022). Each panel corresponds to one taxonomic class. The four observed spectra are shown with vertical display offsets: 2012 QE2 in orange, 2015 FJ98 in blue, 2008 TN215 in green, and the unidentified candidate in magenta. The light-gray curves show the full taxonomic template for context, while the black segments mark the wavelength intervals overlapping each observed spectrum and used in the quantitative comparisons. Shaded regions show the empirical spectral uncertainties. The lowest-mismatch templates are A for 2012 QE2, Z for 2015 FJ98, and B for 2008 TN215 and the unidentified candidate. These results represent limited-wavelength template rankings rather than definitive taxonomic classifications.

The template rankings were evaluated using the mismatch statistic $\chi^2/(N - 1)$, the separation from competing classes, Monte Carlo realizations of the measured spectra, edge-trimming tests, and the absolute quality of the visual and statistical agreement. The Monte Carlo trials test the stability of the ranking under the adopted empirical uncertainties; they do not represent probabilities that an asteroid belongs to a particular class.

The comparison gives different levels of evidence for the four objects. The A representative provides a strong limited-wavelength match for 2012 QE2, with $\chi^2/(N - 1) = 1.12$, a large separation from the next closest template, and the A template preferred in all Monte Carlo trials. The B representative provides a moderate match for 2008 TN215, with $\chi^2/(N - 1) \approx 1.52$, but the wavelength coverage remains short. For 2015 FJ98, the Z representative gives the lowest mismatch, but $\chi^2/(N - 1) = 7.41$ and several red-sloped classes remain visually similar over the restricted F200W interval. The unidentified candidate is also ranked closest to B, but its poor absolute agreement, limited number of usable spectra, and unknown orbit make this only a weak spectral similarity.

Table 5.1 summarizes the template comparison results. The listed classes are the closest matches over the observed NIRISS wavelength intervals, not definitive asteroid types.

Table 5.1: Summary of taxonomic template comparisons for the recovered NIRISS reflectance spectra. The listed classes represent the closest template matches over the observed wavelength intervals, not definitive asteroid types.

Object	Closest template	Other close templates	Interpretation
2012 QE2	A	Z, D, Q, S	Strong A-like limited-wavelength match over the observed F150W interval; not a definitive full-spectrum classification.
2015 FJ98	Z	D, P, X, C	Z-ranked limited-wavelength red spectral similarity; the absolute mismatch is poor, so no secure classification is assigned.
2008 TN215	B	C, Ch, E, K	Moderate B-like limited-wavelength match over the observed F115W interval; the short wavelength coverage prevents a secure full classification.
Unidentified slowly moving candidate	B	C, E, Ch, K	Weak B-ranked limited-wavelength similarity; the absolute mismatch is poor and the source has no secure orbit.

5.3 Object-by-Object Interpretation

5.3.1 2012 QE2 in the Context of the A-Type Asteroid Population

The taxonomic template comparison favored the A representative spectrum for 2012 QE2. Over the reliable F150W interval, the A template gave $\chi^2/(N - 1) = 1.12$, while the next closest template, Z, was separated by $\Delta\chi^2 = 501.07$. The A template also remained preferred in all Monte Carlo trials. This provides strong evidence for an A-like spectral shape over the observed interval, but it does not establish a definitive A-type classification because the spectrum does not cover the full visible-to-near- infrared range or both major silicate absorption regions.

The implications of this match are considered below in the context of the broader A-type asteroid population.

A-type asteroids form a rare taxonomic population characterized by a steep red visible continuum and a broad, deep absorption centered near $1\ \mu\text{m}$, commonly interpreted as evidence for an olivine-dominated surface (Mahlke et al., 2022; Sanchez et al., 2014). In the most olivine-rich cases, the corresponding $2\ \mu\text{m}$ absorption is absent or very weak. However, an A-type classification does not uniquely identify a composition or origin. Detailed visible–near-infrared studies have distinguished nearly monomineralic-olivine objects from olivine-rich objects containing a secondary pyroxene component (Sanchez et al., 2014). Possible meteoritic analogues include brachinites and R chondrites, which represent different degrees and styles of thermal processing. A-type spectra have therefore been associated with differentiated or partially differentiated planetesimals, but they do not by themselves establish that an asteroid is exposed mantle material.

Estimates of the abundance of A-types have varied substantially between surveys. DeMeo et al. (2019) selected candidates using visible-light SDSS measurements and tested them with near-infrared spectroscopy extending across the diagnostic $1\ \mu\text{m}$ absorption. Only approximately one third of the selected candidates were confirmed, demonstrating that visible redness alone is not sufficient for secure classification. Their analysis estimated that A-types represented $0.16 \pm 0.03\%$ of the main-belt population with $H < 17$, approximately corresponding to objects larger than 2 km, or roughly one asteroid in 625. More recently, Delbo et al. (2026) combined Gaia DR3 visible reflectance spectra with classifications based on broader visible–near-infrared observations and obtained an abundance of $2.00 \pm 0.15\%$, approximately one in 50 main-belt asteroids. After accounting for observational biases, they inferred a population of approximately 7,000–8,000 A-types larger than 2 km. The difference of more than an order of magnitude between the two estimates reflects differences in candidate selection, sample size, taxonomic calibration, and population corrections. Although the newer work suggests that A-types are more numerous than previously inferred, both studies identify them as a minority population.

The inferred spatial distribution has also changed as the available sample has increased. DeMeo et al. (2019) obtained central A-type fractions of approximately 0.22%, 0.14%, and 0.11% in the inner, middle, and outer main belt, respectively. Although these values declined outward, their uncertainties overlapped, and the authors found no statistically significant regional concentration. In contrast, Delbo et al. (2026) measured fractions of $3.25 \pm 0.25\%$ for $2.10 \leq a_p < 2.50$ au, $1.91 \pm 0.13\%$ for $2.50 \leq a_p < 2.82$ au, $1.51 \pm 0.13\%$ in the pristine zone ($2.82 \leq a_p < 2.96$ au), and $0.43 \pm 0.04\%$ for $2.96 \leq a_p < 3.25$ au. This outward decrease remained after known family members were removed, supporting an inner-belt concentration that is not produced solely by a few A-type-rich families. These values describe distributions in proper semimajor axis rather than the instantaneous heliocentric distances of individual objects. A-types have been observed over a broad range of inclinations, and the studies considered here do not establish an equally clear population-wide inclination trend.

The evidence for associations with collisional families is similarly dependent on sample size and classification method. DeMeo et al. (2019) identified several A-type objects in or near family regions, including Flora and Gefion, but found no statistically significant enrichment relative to the background population. They also emphasized that orbital stability within a family region does not prove genetic membership because compositionally unrelated interlopers can occupy similar proper elements. The larger analysis of Delbo et al. (2026) instead found substantial family-to-family differences, including A-type fractions of $4.2 \pm 0.5\%$ in Vesta, $3.7 \pm 0.4\%$ in Flora, $0.17 \pm 0.04\%$ in Hygiea, and only $0.003 \pm 0.003\%$ in Themis. The smaller (36256) 1999 XT17 family had an

estimated fraction of $14.1 \pm 3.5\%$. These differences suggest that olivine-rich material may have been produced or exposed in multiple parent populations rather than originating from a single differentiated body. In particular, the enhanced Flora fraction has been interpreted as possible evidence for an inner-belt differentiated or partially differentiated source distinct from Vesta, although individual family associations still require compositional and dynamical confirmation.

Previous mineralogical studies used substantially broader wavelength coverage than is available for 2012 QE2. Near-infrared spectra covering approximately $0.90\text{--}1.65\ \mu\text{m}$ can characterize the $1\ \mu\text{m}$ absorption when combined with visible observations, but they cannot test for a weak $2\ \mu\text{m}$ pyroxene feature (Burbine & Binzel, 2002). Full visible–near-infrared studies extending to approximately $2.5\ \mu\text{m}$ measure the Band I center, Band II strength, and Band Area Ratio to estimate olivine chemistry and the relative abundances of olivine and pyroxene (Sanchez et al., 2014). The spectrum of 2012 QE2 covers only $1.340\text{--}1.661\ \mu\text{m}$ and therefore samples part of the long-wavelength wing of the $1\ \mu\text{m}$ feature while excluding its center, the visible continuum, and the $2\ \mu\text{m}$ region. Its agreement with the A-type representative is therefore consistent with an A-like spectral shape over the observed interval, but is less conclusive than classifications based on complete visible–near-infrared spectra. The present result cannot confirm an A-type classification, determine whether the surface is nearly monomineralic olivine or an olivine–pyroxene mixture, identify a meteorite analogue, or establish a differentiated-mantle origin.

5.3.2 2015 FJ98 in the Context of the Z-Type Asteroid Population

The taxonomic template comparison for 2015 FJ98 did not yield a secure classification. The Z representative spectrum gave the lowest mismatch over the reliable F200W interval, with $\chi^2/(N-1) = 7.41$. The D template was the next closest, separated by $\Delta\chi^2 = 94.98$, and Z remained the preferred template in the Monte Carlo ranking trials. However, the large absolute mismatch and the similar visual behavior of several red-sloped templates, including D, P, X, and C, show that the numerical preference for Z is not a unique physical classification.

The implications of this result are considered below in the context of the broader Z-type asteroid population.

The Z class was introduced by Mahlke et al. (2022) for dark, largely featureless asteroids whose reflectance spectra have steeper red slopes than typical D-types and remain strongly red into the near-infrared. The class is defined observationally rather than by a unique composition. Extremely red spectra have been interpreted as possible evidence for organic-rich or irradiation-processed material similar to that found on some Centaurs and trans-Neptunian objects (Hasegawa et al., 2021). However, impact excavation, space weathering, and surface heterogeneity can also modify spectral slopes and produce differences among observations of the same body (Hasegawa et al., 2022). A Z-type classification therefore does not by itself establish an outer-Solar-System or cometary origin.

In the taxonomy of Mahlke et al. (2022), 23 of 2,125 classified objects, or 1.1%, were assigned to the Z class. Because that catalog was assembled from previously available spectra and albedo measurements, this fraction is not an estimate of the intrinsic Z-type abundance. Using Gaia DR3 visible spectrophotometry, El-Bez-Sebastien et al. (2026) identified 124 main-belt Z-type candidates, including 14 in the inner belt ($2.0 \leq a < 2.5\ \text{au}$), 33 in the middle belt ($2.5 \leq a < 2.82\ \text{au}$), and 77 in the outer belt ($2.82 \leq a < 3.2\ \text{au}$). These candidates represented 0.34% of the Gaia main-belt sample that satisfied the study’s signal-to-noise and albedo-selection criteria. This value describes the selected survey sample and was not fully corrected for discovery and detection biases.

Z-classified objects become considerably more common beyond the main belt. El-Bez-Sebastien et al. (2026) reported sample fractions of 15.5% in the Cybele population and 21.4% among the Hildas. Using visible spectra and the Mahlke et al. (2022) classification scheme, Fornasier & El-Bez-Sebastien (2025) classified 40.6% of the L4 Jupiter Trojans and 42.1% of the L5 Trojans as Z-types. Although the individual percentages depend on each survey’s wavelength coverage, selection criteria, and taxonomy, the combined results show that very red, low-albedo objects are substantially more prevalent in the outer asteroid populations than in the main belt.

No comparably clear class-wide dependence on inclination or eccentricity has been established. El-Bez-Sebastien et al. (2026) found no significant overall relationship between these orbital elements and the measured physical properties of the main-belt candidates. A subset of 18 Z-classified objects across the main-belt, Cybele, and Hilda populations had relatively large eccentricities and inclinations together with Tisserand parameters with respect to Jupiter below 3. These properties may be consistent with comet-like dynamical histories for part of the population, but they do not demonstrate a cometary origin for Z-types as a class.

The Gaia-classified candidates had a mean visible geometric albedo of approximately 7.9%, consistent with generally dark surfaces. Their mean albedo decreased weakly with semimajor axis, while the measured diameters increased outward. The diameter trend is at least partly affected by observational selection because small objects become more difficult to detect at larger distances. Nineteen main-belt candidates were associated dynamically with 13 collisional families, but none of the families was dominated by Z-types. Because many of these families have characteristic taxonomies unlike Z, some of the associated objects may be dynamical interlopers rather than fragments of the family parent bodies (El-Bez-Sebastien et al., 2026).

The inferred abundance of Z-types also depends strongly on the method used to identify them. Broadband colors and visible spectra can select objects with exceptionally red slopes, but red visible colors alone do not establish how the spectrum behaves at longer wavelengths. Gaia DR3 provides a large and internally consistent spectrophotometric sample, but its wavelength coverage ends near $1.03\ \mu\text{m}$. D- and Z-type spectra can overlap over this visible interval, while the longer-wavelength slope and curvature provide additional separation. Visible–near-infrared spectroscopy extending to approximately $2.5\ \mu\text{m}$ has shown that some extremely red objects flatten beyond approximately $1.5\ \mu\text{m}$, whereas others continue to increase in reflectance (Humes et al., 2024). Near-infrared observations are therefore needed to confirm individual Gaia or color-selected candidates and to determine whether their full spectral shapes are consistent with the Z class.

The spectrum of 2015 FJ98 covers only $1.754\text{--}2.215\ \mu\text{m}$ and therefore samples the long-wavelength portion of the reflectance spectrum without measuring the steep visible slope or the transition between the visible and near-infrared regions. Its best representative-template match was the Z class, but the relatively large mismatch, $\chi^2/(N - 1) = 7.41$, indicates that the Z representative does not provide a good absolute description of the measured spectrum. The positive slope of 2015 FJ98 agrees qualitatively with the long-wavelength redness observed for some Z-classified asteroids, but the restricted wavelength range and poor template fit make this result less conclusive than previous classifications based on combined visible and near-infrared spectra.

5.3.3 2008 TN215 and the Unidentified Candidate in the Context of the B-Type Asteroid Population

The taxonomic template comparison for 2008 TN215 favored the B representative spectrum among the tested templates. The B template remained the lowest-mismatch comparison after unreliable edge bins were removed, indicating that the preference was not driven only by filter-edge behavior. Using the empirical wavelength-dependent scatter as the uncertainty, the trimmed comparison gave $\chi^2/(N - 1) \approx 1.52$, with C as the next closest class. Monte Carlo trials also selected B in all realizations, showing that the relative ranking is stable. The result is nevertheless a limited-wavelength comparison rather than a firm B-type classification.

The 2008 TN215 spectrum also shows a shallow depression near $1.17\ \mu\text{m}$. To test whether this structure could be interpreted as an absorption feature, the reflectance in the $1.16\text{--}1.18\ \mu\text{m}$ region was compared with nearby continuum windows. The resulting depression had a significance of approximately 2.1σ . A similar dip was present across the retained TN215 difference spectra, suggesting that the feature is not caused by a single extraction alone. However, because the significance remains below the usual 3σ threshold, the depression is treated as marginal rather than as a diagnostic absorption band.

The template comparison for the unidentified slowly moving candidate also favored a B-like spectral shape, with C, E, Ch, and K among the closest competing templates. The recovered spectrum is approximately flat over the usable F115W interval, with small-scale bin-to-bin variations. Only two usable ordered spectra were available, and the apparent structure near $1.17\ \mu\text{m}$ was not reproduced consistently between them. The B ranking remained stable in the comparison tests, but the absolute agreement was poor. The result is therefore best described as a weak B-like limited-wavelength spectral similarity, not a firm taxonomic classification.

The main scientific value of this object is the demonstration that a slowly moving source can be recovered in archival NIRISS WFSS data and converted into a relative reflectance spectrum. Its orbit is not securely determined. Follow-up astrometric identification or orbit fitting would be required before its dynamical class and physical interpretation could be established.

B-type asteroids are generally dark, primitive objects characterized by flat-to-blue visible reflectance spectra and a decrease in reflectance toward near-ultraviolet wavelengths. Their physical interpretation is commonly associated with carbonaceous material, but the class does not represent a single composition, hydration state, or thermal history. The definition also depends on the taxonomic system. In the Tholen taxonomy, B- and F-types are distinguished partly by the strength of their near-ultraviolet downturn, whereas several later taxonomies combined them because their wavelength coverage did not extend far enough into the ultraviolet. Furthermore, objects with similar blue visible spectra exhibit a wide range of spectral slopes from 0.8 to $2.5\ \mu\text{m}$, demonstrating that the visible B-type label does not uniquely predict near-infrared behavior (de León et al., 2012).

Previous studies have therefore used several complementary observing methods. Visible colors and spectroscopy can identify blue spectral slopes, but provide limited constraints on longer-wavelength spectral diversity and can be insufficient to distinguish B- from F-types when near-ultraviolet data are unavailable. de León et al. (2012) combined new $0.8\text{--}2.5\ \mu\text{m}$ spectra with published visible and near-infrared observations to study 45 broadly defined B-types. This broader wavelength coverage revealed a continuous range from blue to red near-infrared slopes and allowed comparisons with carbonaceous meteorites, but did not establish a unique meteorite analogue for the class. More recently, Tiaut-Ruano et al. (2026) used Gaia DR3 spectrophotometry, including near-ultraviolet information, together with visible albedo measurements to distinguish B- and F-types in a large,

internally consistent sample. Gaia nevertheless extends only to approximately $1.03\ \mu\text{m}$ and therefore cannot measure the full near-infrared diversity identified by ground-based spectroscopy.

Within a selected Gaia catalog of 14,042 asteroids, Tinaut-Ruano et al. (2026) classified 271 objects as B-types. These included 16 in the inner belt, 53 in the middle belt, and 199 in the outer belt, with two objects in the Cybele region and one Jupiter Trojan. B-types represented approximately 0.37%, 1.17%, and 4.57% of the selected inner-, middle-, and outer-belt samples, respectively. These results show that B-types are most prevalent in the outer main belt within the Gaia sample. However, the percentages depend on the study’s spectral-quality and albedo-selection requirements and were not intended as fully debiased estimates of the intrinsic asteroid population.

The observed orbital distribution is strongly influenced by collisional families rather than following a simple class-wide trend. A major low-inclination concentration occurs in the outer belt within the Themis family, which occupies approximately $3.05 \leq a \leq 3.22\ \text{au}$, $0.12 \leq e \leq 0.19$, and $0.7^\circ \leq i \leq 2.22^\circ$ and contains many primitive C- and B-type objects (Fornasier et al., 2016). A second concentration is associated with the much higher-inclination Pallas family in the central belt. The limited spectroscopic sample examined by Carruba (2010) was broadly compatible with a B-type family composition, although two of seven classified objects were C-types and could be interlopers. Because prominent B-type populations occur at both low and high inclinations, the class cannot be described as preferentially occupying either inclination regime. Consistent with this picture, de León et al. (2012) found no significant class-wide relationship between near-infrared spectral behavior and semimajor axis, eccentricity, inclination, size, or heliocentric distance.

Thermal-infrared observations provide additional physical constraints that spectroscopy alone cannot supply. Using WISE measurements of 111 main-belt objects, Alí-Lagoa et al. (2013) obtained a mean visible geometric albedo of

$$\overline{p_V} = 0.07 \pm 0.03$$

for the broadly defined B-type sample. The Pallas family was substantially brighter, with

$$\overline{p_V} = 0.14 \pm 0.05,$$

supporting the interpretation that it is physically distinct from much of the broader population. The Themis family also displays substantial variation in visible slope and albedo, while members of the younger Beagle subfamily tend to be bluer and somewhat brighter than older Themis members (Fornasier et al., 2016). Comparisons between visible and infrared albedos have been used to suggest that a broad $3\ \mu\text{m}$ absorption may be common among B-types, but such photometric measurements do not uniquely identify the absorbing material or establish the hydration state of an individual asteroid (Alí-Lagoa et al., 2013).

The spectrum of 2008 TN215 covers only approximately $0.89\text{--}1.16\ \mu\text{m}$. It therefore excludes the near-ultraviolet region used to distinguish B- from F-types, samples only the beginning of the $0.8\text{--}2.5\ \mu\text{m}$ spectral diversity measured in previous studies, and contains no information about a possible $3\ \mu\text{m}$ absorption. The present analysis also does not provide an independent albedo measurement. Its best match to the B-type representative, with $\chi^2/(N - 1) \approx 1.52$, indicates a moderate agreement over the observed interval, but cannot determine whether the spectrum remains blue, becomes neutral, or turns red at longer wavelengths. The result therefore agrees with a B-like spectral shape over the restricted JWST range but is less conclusive than previous classifications based on near-ultraviolet, visible, full near-infrared, and albedo measurements.

The unidentified candidate provides still less compositional information than 2008 TN215. Its short, noisy F115W spectrum and poor absolute template agreement support only a weak B-like comparison.

Because the source also lacks a secure orbit and independent albedo information, the taxonomic ranking does not support a specific population, composition, or origin.

5.4 Reliability and Limitations

Several limitations affect the strength of the spectral interpretations in this work. Spectral bins near filter response edges require caution. In these regions, small count-rate errors can be amplified by the response correction, producing artificial rises or drops in reflectance. For this reason, edge-affected bins were trimmed or excluded from physical interpretation. The final interpretations are based on the wavelength regions where the spectra were most repeatable and least affected by response-edge behavior.

The wavelength solutions are approximate. They rely on field-star validation and linear wavelength endpoint transfer rather than a full object-specific spectral WCS solution. This is sufficient for broad continuum comparisons, but it limits the confidence with which small-scale spectral features can be assigned to specific wavelengths.

The plotted uncertainties do not include every possible systematic effect. They describe extraction uncertainty and spectrum-to-spectrum variation, but they do not fully include systematic uncertainty from wavelength calibration, response correction, solar division, background residuals, or template mismatch. For this reason, the taxonomic comparisons should be interpreted as relative template rankings rather than formal taxonomic classifications.

Finally, reversed difference products are useful repeatability checks, but they are not fully independent observations. They are derived from the same underlying integrations, so agreement among them increases confidence in the recovered spectral shape but does not remove all shared systematic errors.

Despite these limitations, the results show that serendipitous moving objects in JWST/NIRISS WFSS data can be recovered and converted into usable relative reflectance spectra. Difference imaging suppresses the fixed background field and allows moving spectral traces to be isolated, even when the objects were not the primary targets of the observations.

This work suggests that archival slitless spectroscopy can provide additional small-body spectral measurements without requiring new dedicated observations. The approach is especially valuable for objects that pass through existing JWST fields by chance, including faint or slowly moving sources that may not have been targeted directly. These serendipitous spectra can provide broad compositional constraints and help identify objects that are worth follow-up with more complete wavelength coverage.

5.5 Future Work

Future work should extend this analysis in two main directions. The first is to identify which NIRISS WFSS blocking filter provides the most taxonomic information for small-body spectra. The results in this thesis show that a single filter can recover useful continuum information, but that classification can remain ambiguous when the observed wavelength interval samples only a smooth part of the spectrum. This was especially clear for 2015 FJ98, where several templates showed similar visual agreement with the red continuum over F200W.

For future NIRISS WFSS observations aimed at asteroid classification, F115W is likely the most

useful single filter. Although F200W covers a wider wavelength interval, F115W samples the region just longward of $1\ \mu\text{m}$, where many asteroid taxonomic templates show stronger differences in slope and curvature. This region also provides leverage on the short-wavelength side of broad silicate absorption structure. Therefore, F115W may separate some classes more effectively than filters that mainly sample smoother continuum regions.

Mahlke et al. taxonomic templates with NIRISS WFSS filter ranges

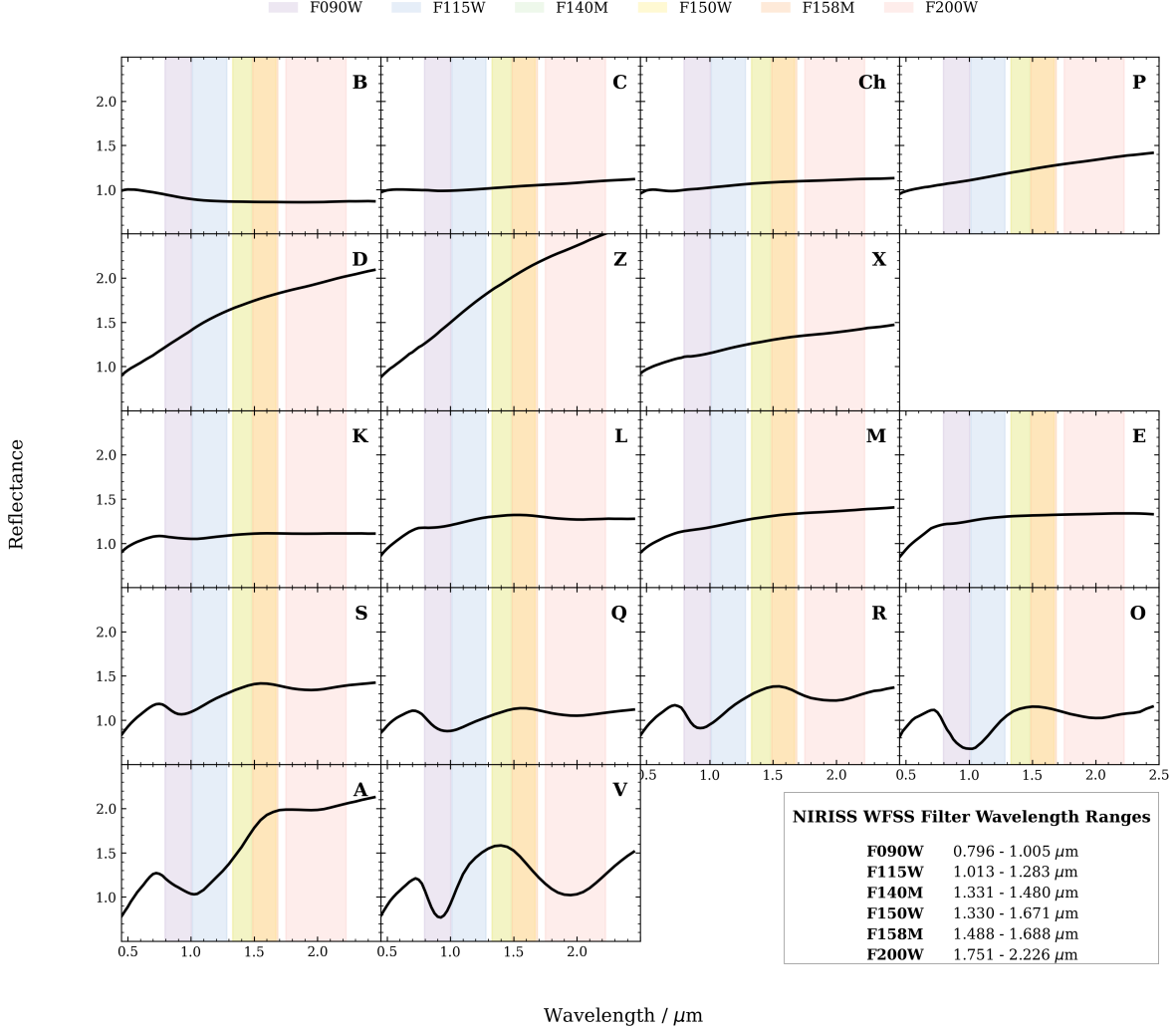


Figure 5.2: Mahlke et al. taxonomic representative spectra with the approximate NIRISS WFSS filter wavelength ranges overlaid. The F115W filter samples the region just longward of $1\ \mu\text{m}$, where several classes show stronger differences in slope and curvature. This makes F115W a useful single-filter choice for future NIRISS WFSS observations aimed at taxonomic discrimination, although multiple filters would still be required for more secure classification.

A more quantitative version of this test would compare the taxonomic templates within each NIRISS WFSS filter separately. For each filter, the templates could be restricted to that wavelength range and compared using the same normalization and comparison procedure used in this thesis. The filters could then be ranked by the separation in χ^2 between the best and next-best classes, or by

the number of classes that remain distinguishable at a given signal-to-noise ratio. This would turn the qualitative filter choice into a quantitative observing recommendation.

If only one NIRISS WFSS filter can be used, F115W is the best candidate for maximizing class information. If two filters are possible, F115W and F200W would provide stronger leverage by sampling both the 1 and 2 μm regions. If three or more filters are possible, F115W, F150W, and F200W should be prioritized, with F090W added when the goal is to better constrain the blue side of the 1 μm region.

The second major extension is to process all available exposures for each field. This thesis analyzed one representative exposure for each asteroid or field. However, the 2012 QE2 field and the 2008 TN215 field each contain additional NIRISS WFSS exposures. Processing those exposures would provide a stronger test of whether the same continuum shapes and template rankings are recovered independently.

Combining all available exposures would improve the signal-to-noise ratio and provide a better check on exposure-to-exposure systematics. It would also test whether the recovered spectral shapes are stable against changes in detector position, background structure, trace overlap, and wavelength placement. For 2008 TN215 and the unidentified slowly moving candidate, processing the full field would be especially useful because both sources appear in the same field. The additional exposures could therefore strengthen both the spectral interpretation and the astrometric interpretation of the unidentified source.

For the unidentified slowly moving candidate, future work should also focus on astrometric identification. If the source can be recovered at multiple times, its motion can be measured more accurately. This would improve the chance of matching it to a known object or constraining its possible orbit. Until that step is complete, the source should be treated as an unidentified slowly moving candidate, not as a confirmed distant Solar System object.

Chapter 6

Conclusion

This thesis tested whether serendipitously observed moving Solar System objects in archival JWST/NIRISS wide field slitless spectroscopy data can be recovered and converted into useful relative reflectance spectra. The work developed and applied a custom extraction procedure based on difference imaging, trace aperture extraction, local background subtraction, response correction, and division by a solar spectrum. The goal was not only to detect the moving objects, but also to determine whether their recovered spectra contain scientifically useful information about surface color and possible taxonomic class.

The main result is that NIRISS WFSS data can recover relative reflectance spectra for serendipitous moving objects, even when those objects were not the primary targets of the observations. Difference imaging was especially useful because it suppressed the fixed background field and isolated the motion of the asteroid spectra between integrations. This made it possible to extract spectra for 2012 QE2, 2015 FJ98, 2008 TN215, and an unidentified slowly moving candidate.

The recovered spectra showed different near infrared continuum behaviors. 2012 QE2 showed a repeatable positive continuum slope over the F150W wavelength range, and its spectrum was strongly matched by the A taxonomic template over the observed interval. 2015 FJ98 also showed a strong red continuum over the F200W wavelength range, but its taxonomic interpretation remained ambiguous because several templates provided similar visual agreement with the measured slope. In contrast, 2008 TN215 and the unidentified slowly moving candidate showed negative continuum slopes over the F115W range, with B like templates providing the closest matches. No object showed a repeatable, securely detected absorption feature within the recovered wavelength coverage.

These results should be interpreted as broad spectral constraints rather than definitive taxonomic classifications. The spectra cover only limited wavelength intervals, and the complete 1 and 2 μm absorption bands commonly used in asteroid mineralogical interpretation are not observed. The wavelength solutions are approximate, the response correction can amplify edge behavior, and the uncertainties do not capture all possible systematic effects. For these reasons, the strongest scientific conclusions are the repeatable continuum slopes and the relative template preferences, not firm compositional assignments.

A key implication of this work is that archival JWST slitless spectroscopy can provide additional small body spectral measurements without requiring new dedicated asteroid observations. Serendipitous moving objects that pass through existing JWST fields can contain recoverable spectral information, especially when multiple integrations allow difference products to be formed. This method is most reliable for broad continuum slopes and repeatability tests. It is less secure for narrow absorption

features unless they appear at the same wavelength in multiple independent products and lie away from filter edges, trace overlap, and background residuals.

This thesis also identifies clear directions for future work. The most immediate extension is to process all available exposures for each field, rather than one representative exposure. This would test whether the recovered spectral slopes and template rankings are stable across independent exposures, and would improve the signal to noise ratio of the final spectra. For the unidentified slowly moving candidate, additional exposures could also improve the astrometric constraint and help determine whether the source can be matched to a known object.

Future observations aimed specifically at asteroid classification should also choose NIRISS WFSS filters based on taxonomic leverage, not only wavelength coverage. The template comparison suggests that F115W is likely the best single filter for class discrimination because it samples the region just longward of $1\ \mu\text{m}$, where many taxonomic classes begin to differ in slope and curvature. However, multiple filters would provide stronger constraints. Combining F115W with F150W and F200W would better connect local continuum color to the broader near infrared spectral shape.

Overall, this work demonstrates that serendipitous JWST/NIRISS WFSS observations can be used to recover and interpret moving object spectra. The method is not yet a replacement for dedicated asteroid spectroscopy, but it provides a practical way to extract additional compositional information from existing archival data. As the JWST archive grows, this approach can expand the number of small bodies with near infrared spectral constraints and help identify objects that deserve more complete follow up observations.

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