UV COLOURS OF ASTEROIDS IN THE SERENDIPITOUS OBSERVATIONS OF THE XMM-NEWTON OPTICAL MONITOR CAMERA.



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2 Resumen

El presente documento expone el trabajo realizado como parte del Trabajo Fin de Máster del Máster Universitario en Astronomía y Astrofísica de la Universidad Internacional de Valencia: "UV COLOURS OF ASTEROIDS IN THE SERENDIPITOUS OBSERVATIONS OF THE XMM-NEWTON OPTICAL MONITOR CAMERA" ("COLORES ULTRAVIOLETA DE ASTEROIDES EN OBSERVACIONES SERENDÍPICAS DEL OPTICAL MONITOR CAMERA DEL XMM-NEWTON").

El telescopio espacial de la Agencia Espacial Europea (ESA), XMM-Newton (X-ray Multi-Mirror Mission)¹, lanzado en 1999 ha realizado (y sigue realizando hasta la fecha) observaciones en longitudes de onda corta, centrándose sobre todo en rayos X y ultravioleta (UV). Éstas últimas llevadas a cabo por su telescopio óptico/UV: el XMM-OM (XMM-Newton Optical/UV Monitor Telescope). A lo largo de las últimas décadas, dicho instrumento se ha utilizado para la observación con carácter científico de objetivos específicos en el rango óptico y UV. No obstante, tal cantidad de observaciones a lo largo de los años abren la posibilidad a observaciones serendípicas (casuales, no intencionadas) de otros cuerpos celestes.

El objeto de este trabajo es el análisis de asteroides en dichas observaciones serendípicas. Está basado en el estudio previo realizado por la directora del TFM², donde se publicó un catálogo de observaciones que podrían haber capturado un asteroide en su campo de visión de forma inintencionada. En el presente trabajo se han analizado varias de estas posibles observaciones atendiendo al rango óptico/UV, procediendo a analizar fotométricamente aquellas que proporcionaban suficiente información.

En esta memoria se recogen no sólo los resultados del estudio, sino también la metodología seguida para llegar a ellos, tanto desde un punto de vista científico como

¹ Technical Details - OM - XMM-Newton - Cosmos. (2000, 01 01). cosmos.esa.int. https://www.cosmos.esa.int/web/xmm-newton/technical-details-om

² Racero, E. et al (2022). ESASky SSOSS: Solar System Object Search Service and the case of Psyche. *Astronomy & Astrophysics*, *659*, A38.



práctico, desglosando cada una de las herramientas desarrolladas para facilitar (e incluso automatizar) el proceso.



3 List of Acronyms

Acronym		
API	Application Programming Interface	
DS9	SAOImageDS9 software	
ESA	European Space Agency	
FITS	Flexible Image Transport System	
FoV	Field of View	
HDU	Header Data Unit	
HST	Hubble Space Telescope	
НТТР	Hypertext Transfer Protocol	
I/O	Input/Output	
(XMM-Newton) OM	XMM-Newton Optical/UV Monitor Telescope	
SSO	Solar System Object	
(ESASky) SSOSS	(ESASky) Solar System Object Search Service	
UV	Ultraviolet	
(ESA) XMM-Newton	(ESA) X-ray Multi-Mirror Mission	
XSA	XMM-Newton Science Archive	



4 Introduction

4.1 Scientific background



4.2 Previous work

The present work leverages on ESASky Solar System Object Search Service (ESASky SSOSS)³, a catalogue listing all potential detections of asteroids within estimated limiting magnitude or flux limit in Herschel, XMM-Newton (X-ray Multi-Mirror Mission) and HST (Hubble Space Telescope).

Observations for all three above-mentioned missions were geometrically cross-matched against ESASky 800,000 asteroids and 2,000 comets. Each one of the potential serendipitous observations was classified according to the likelihood of the Solar System Object (SSO) position (either at the start or end of the observation), being included in the field of view (FoV) footprint:

- Type 1: the position of the SSO does not lie within the FoV footprint, but its uncertainty overalls with it.
- Type 2: the position of the SSO lies within the FoV footprint.
- Type 3: neither starting nor ending positions of the SSO lie within the FoV footprint, but the SSO path during the observation crosses the FoV footprint.

The catalogue was made available in 2021 and listed 909 serendipitous detections in Herschel images, 985 in XMM-Newton Optical Monitor camera images, and over 32,000 potential serendipitous detections in HST images.

For the purpose of this Master's Thesis objective, we are primarily interested in serendipitous observations of SSO in the Optical/UV range. The table below outlines the

³ Racero, E. et al (2022). ESASky SSOSS: Solar System Object Search Service and the case of Psyche. *Astronomy & Astrophysics*, *659*, A38.



number of potential serendipitous observations by XMM-Newton Optical/UV Monitor Telescope (XMM-Newton OM), broken down for each one of its colour discriminating broad-band filters:

Instrument	Zero-Point ^a	N _{total}	N _{serend}
OM V	-0.0474	4038	216
OM B	-0.6028	3939	428
OM U	-0.7439	7792	431
OM UVW1	-1.4842	16501	294
OM UVM2	-4.0778	13112	9
OM UVW2	-3.6144	6605	3

ESASKy SSOS number of potential XMM-OM (N_{serend}) serendipitous observations for each colour discriminating broad-band filter⁴.

4.3 XMM Newton

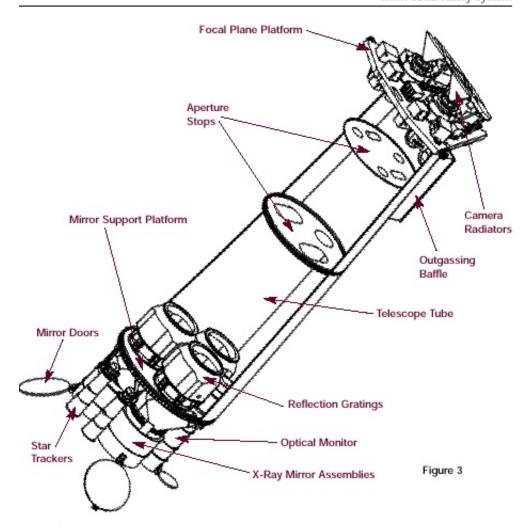
The European Space Agency's (ESA) X-ray Multi-Mirror Mission (XMM-Newton) was launched on December 10th 1990. It constituted ESA's second cornerstone of the Horizon 2000 Science Programme⁵.

At 4 tonnes, and 10 metres, the XMM-Newton spacecraft is the largest scientific satellite ever launched by the European Space Agency. It carries 3 high throughput X-ray telescopes, as well as an optical monitor.

⁴ Racero, E. et al (2022). ESASky SSOSS: Solar System Object Search Service and the case of Psyche. *Astronomy & Astrophysics*, *659*, A38.

⁵ *The Science Programme*. (n.d.). European Space Agency. https://www.esa.int/esapub/br/br114/br114sci.htm





XMM-Newton spacecraft⁶.

Earth's atmosphere blocks out all X-rays, thus only a telescope in space can actually detect and observe celestial X-ray sources. As of May 2022, XMM-Newton sits at a tilted (~70 deg inclination) highly eccentric orbit, with a perigee around 26,000 km and an apogee around 100,000 km, resulting in an orbital period of approximately 48 hours⁷. Due to the radiation background from the radiation belts, XMM-Newton's instruments are limited to altitudes above 46,000 km, i.e. roughly 40 hours of operational time each orbit⁸.

⁶ Technical Details - Spacecraft - XMM-Newton - Cosmos. (n.d.). cosmos.esa.int. https://www.cosmos.esa.int/web/xmm-newton/technical-details-spacecraft

⁷ 4.1 XMM-Newton orbit. (n.d.). European Space Agency.

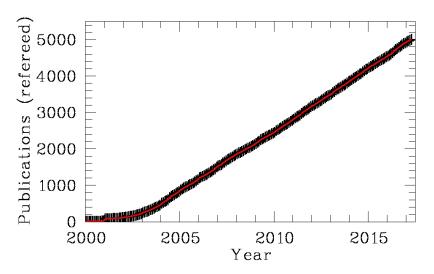
https://xmm-tools.cosmos.esa.int/external/xmm_user_support/documentation/uhb/orbit.html

⁸ ESA Science & Technology - Orbit/Navigation. (n.d.). ESA Science & Technology. https://sci.esa.int/web/xmm-newton/-/31349-orbit-navigation



XMM-Newton's mission is aiding the scientific community in solving a number of cosmic mysteries. Scientists can therefore apply for observing time on XMM-Newton, which are granted on a competitive basis.

Even today, more than 20 years after its launch, XMM-Newton keeps providing useful data for the scientific community. As of 2017 the XMM-Newton observatory had already reached 5,000 science papers in the referred literature⁹.



Number of XMM-Newton publications in refereed journals.

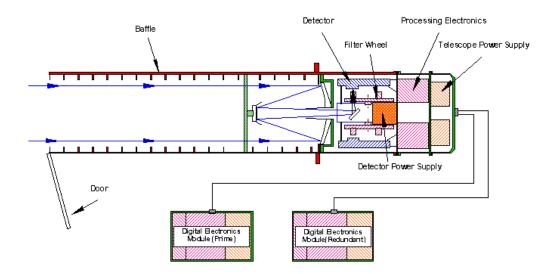
4.3.1 Optical/UV Monitor Telescope

The Optical/UV Monitor Telescope (XMM-OM or OM) provides coverage between 170 nm and 650 nm. It consists of a Telescope Module and a separate Digital Electronics Module. The former contains the optics and detectors, the latter houses the Instrument Control Unit (in charge of communication with the spacecraft and commanding of the instrument) as well as the Data Processing Unit (which carries out the pre-processing of the data before it is sent to the ground)¹⁰.

⁹ 5000 Papers - XMM-Newton. (n.d.). cosmos.esa.int. https://www.cosmos.esa.int/web/xmm-newton/5000-papers

¹⁰ *Technical Details - OM - XMM-Newton - Cosmos.* (n.d.). cosmos.esa.int. https://www.cosmos.esa.int/web/xmm-newton/technical-details-om





A schematic of the Optical/UV Monitor Telescope.

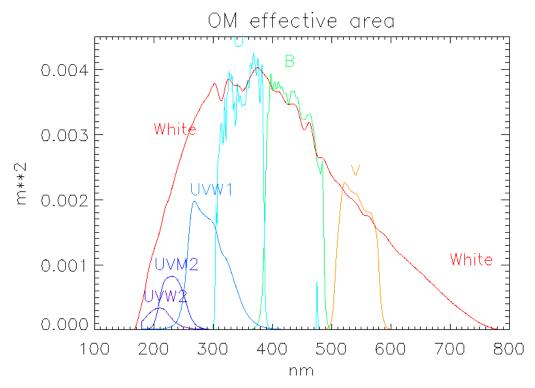
Some of OM's main characteristics:

- 2m long telescope tube.
- 30cm aperture Ritchey-Chretien telescope.
- f/12.7 focal ratio.
- 3.8m focal length.
- 6 broad band filters.

The 6 broad band filters for colour discrimination in the UV and optical, cover the wavelength range between 180 nm and 580 nm¹¹:

¹¹ Filter Wheel - XMM-Newton - Cosmos. (n.d.). cosmos.esa.int. https://www.cosmos.esa.int/web/xmm-newton/om-filter





Throughput curves for the OM filters, folded with the detector sensitivity¹².

The following table outlines the 6 colour discrimination broad band filters as well as their alternative nomenclature used throughout the present document:

Filter	Colour discrimination	Alternative name
UVW2	UV	S
UVM2	υv	М
UVW1	uv	L
U	Optical	U
В	Optical	В
V	Optical	V

XMM-OM colour discrimination filters nomenclature.

¹² Bands - XMM-Newton - Cosmos. (n.d.). cosmos esa. https://www.cosmos.esa.int/web/xmm-newton/om-filter-bands



4.4 Objective

As XMM-Newton Optical/UV Monitor Telescope continues gathering information and serving specific observation requests from the scientific community, the chances of it unintentionally observing asteroids (i.e. 'by chance') increases. The objective of this Master's Thesis is to leverage previous work in the area to try and obtain Optical/UV colours for some of the asteroids observed serendipitously.

The process to achieve this objective can be outlined as:

- 1. Selection of candidate observations: during this step, we shortlist the observations provided by ESASky SSOSS that could contain data in line with our objective.
- 2. Screening: at this point the observations shortlist is shrinked further to exclude any instance with none or insufficient data.
- 3. Photometry: a calibrated magnitude in both optical and UV is obtained for the observations that passed the screening.

The next chapter ('Methodology') details each one of the above-mentioned steps.



5 Methodology

This section describes the end-to-end process carried out. It's presented in a sequential manner:

- Candidates selection: describes which and how the candidate for serendipitous observations were filtered.
- Screening: describes how actual serendipitous observations are set aside from the non-promising candidates.
- Photometry: walks through the photometric process of said serendipitous observations.

5.1 Candidates selection

We refer to "candidates" as those observations that could potentially include a non-targeted Solar System Object (SSO) in their field of view (FoV), capturing data in wavelengths that might be of interest. The candidate selection leverages on previous work, the Solar System Object Search Service (SSOSS) catalogue for XMM-Newton OM, which provides up to 985 potential serendipitous detections¹³:

Instrument	Zero-Point ^a	N _{total}	N _{serend}
OM V	-0.0474	4038	216
OM B	-0.6028	3939	428
OM U	-0.7439	7792	431
OM UVW1	-1.4842	16501	294
OM UVM2	-4.0778	13112	9
OM UVW2	-3.6144	6605	3

ESASKy SSOS number of potential XMM-OM (N_{serend}) serendipitous observations for each colour discriminating broad-band filter.

These 985 potential detections were filtered out considering:

- Geometrical constraints assessing whether the SSO could have been in the instrument FoV.

¹³ Racero, E. (2022). ESASky SSOSS: Solar System Object Search Service and the case of Psyche. *Astronomy & Astrophysics*, *659*, A38.



- Instrumental constraints assessing whether the SSO apparent magnitude as seen from the instrument would be above its detection threshold.

The list of 985 observations is then trimmed further attending to the wavelengths (i.e. filters) of interest. We'll be considering observations that fulfil both of the following conditions:

- The observation used one or more of filters S, M and/or L.
- The observation used one or more of filters U, B and/or V.

After applying the above-mentioned constraints, the list is reduced down to 95 candidate observations (which can be found in the Annexes section) that satisfy them in one way or another. This will constitute the final list of candidates that will be subject to the screening process.

N	observation	sso_name	ra1	dec1	ra2	dec2	filters
1	0012440101	Lictoria	13.99603658	-1.415317889	14.07883767	-1.363111917	L;B
2	0081340801	Stepanov	183.3527003	2.7053835	183.433249	2.687358	L;U;B
3	0106660601	1994 UF2	333.6775958	-17.72910939	333.9756773	-17.53652372	L;U
4	0110980101	Lucubratio	170.061614	13.66864472	170.2531624	13.58085442	L;B
5	0110980601	1030 T-1	199.8925842	-14.85586353	200.1011217	-14.91287867	L;U;B
6	0111170101	Velichko	98.05291688	17.67519933	98.37874979	17.70504883	L;V

A subset of the final 95 candidate observations. The full table can be found in the Annexes section.

5.2 Screening

This section describes the work and process used to filter out candidates from actual detections. None of the shortlisted 95 are guaranteed to contain serendipitous detections so further analysis is needed.

A Python¹⁴ piece software was written to help with the screening process by partially automating some of its stages.

¹⁴ (n.d.). Welcome to Python.org. https://www.python.org/



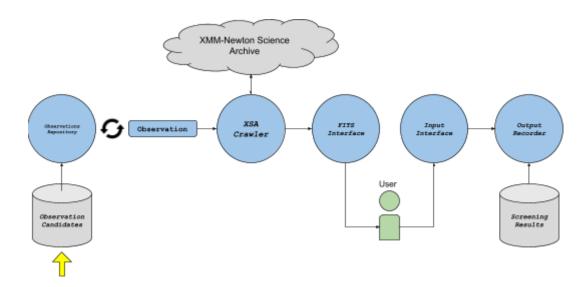


Diagram of the screening process.

The diagram above outlines the different software *entities* that take part in automating the screening process:

- A starting list of Observation Candidates is made available by an Observations Repository.
- 2. The *Observations Repository* is iterated over, providing *Observation* instances. For each one of this instances:
 - 2.1. A XMM-Newton Science Archive Crawler (*XSA Crawler*) obtains the images related to the observation.
 - 2.2. The FITS¹⁵ (Flexible Image Transport System) Interface displays the downloaded images to the user for them to analyse.
 - 2.3. The user's input is recorded by the *Input Interface* and sent over to the *Output Recorder*, which will update and persist the *Screening Results*.

Each one of the above-mentioned *entities* is abstracted, so that one can plug and play different implementations without breaking the entire process. For instance, the *FITS Interface* might have an implementation using a Python FITS library or it might be opening a process to call an external binary (e.g. DS9¹⁶).

¹⁵ (2021, January 17). FITS Support Office. https://fits.gsfc.nasa.gov/fits_home.html

¹⁶ (n.d.). SAOImageDS9. https://sites.google.com/cfa.harvard.edu/saoimageds9



5.2.1 Obtaining the observation data

The XMM-Newton Science Archive (XSA)¹⁷ provides both a web-based user interface¹⁸ as well as an HTTP-based (Hypertext Transfer Protocol) API¹⁹ (Application Programming Interface) to obtain XMM-Newton data. XSA has served as the resource of the candidate observations.

```
class Crawler:
    """XMM-Newton Science Archive (XSA) crawler interface.
    """

def crawl(self, observation: observation.Observation) -> Dict[str, List[str]]:
    """Obtains the images of the specified observation and filters.

Args:
    observation (observation.Observation): observation to be obtained

Returns:
    Dict[str, List[str]]: a key-value structure containing filter as keys and the list of corresponding file paths as a list. Filters with no files will not be included in the results (no key).
    """
    pass
```

XMM-Newton Science Archive Crawler.

An HTTP-based implementation of the *Crawler* interface was used to automate the process of downloading all the relevant data related to a given observation. The data is downloaded locally for it to be displayed and analysed on the next step of the process.

5.2.2 Displaying the data

Since the outlined process involves a user-in-the-loop, the data (images) are to be displayed for said user to analyse them.

¹⁷ XMM-Newton Science Archive - XMM-Newton. (n.d.). cosmos esa. https://www.cosmos.esa.int/web/xmm-newton/xsa

¹⁸ Rodríguez, P. (n.d.). XMM-Newton Science Archive. http://nxsa.esac.esa.int/nxsa-web/#search

¹⁹ Rodríguez, P. (n.d.). XMM-Newton Science Archive. http://nxsa.esac.esa.int/nxsa-web/#aio



```
class Interface:
    """Flexible Image Transport System (FITS) user interface (UI)."""

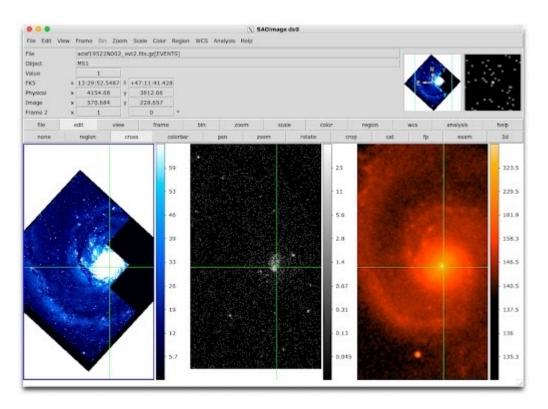
def display(self, fits_paths: List[str], observation: observation.Observation = None):
    """Displays the specified FITS corresponding to the specified observation.

Args:
    fits_paths (List[str]): list of FITS paths
    observation (observation.Observation): the corresponding observation.
    Defaults to None.
    """
    pass

def close_current_display(self):
    """Closes the current display."""
    pass
```

Flexible Image Transport System (FITS) Interface.

DS9²⁰ is an image display and visualisation tool for astronomical data. A DS9-based implementation was used during the screening due to the familiarity with the software and the capabilities it offers.



DS9 user interface.

²⁰ (n.d.). SAOImageDS9. https://sites.google.com/cfa.harvard.edu/saoimageds9



DS9 offers command line options²¹ to interact with it programmatically. This allowed further automation of the overall screening process, opening DS9 with the relevant set of frames to be analysed with the desired set of parameters.

The one (and so far only) disadvantage of including DS9 as part of the automated screen process is its lack of interactiveness, i.e. once a DS9 instance has been opened via command line, there are no means to interact with it. In order to change any of its current state, (e.g. frames, zoom, etc.) one must close and reopen a new process. This, although saving time overall compared to a manual process, makes the screening a bit slower.

On the other hand, amongst the desired set of parameters above-mentioned, there were some that considerably improved the detection job:

- Trajectory indicators
- Scale adjustment

5.2.2.1 Trajectory indicators

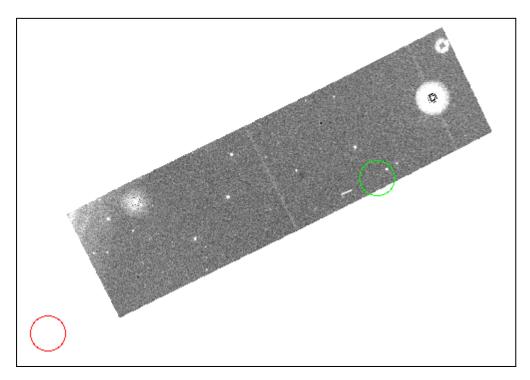
DS9 "Regions" package²² offers means to overlay shapes on the image. This is used, together with the information from the survey regarding the likely starting and ending position of the object, to display the potential starting and ending point of the object's trajectory.

The object, if present, is not necessarily likely to be found within the starting or ending area, but somewhere along the line that joins them both. This greatly helps the user focus on the likely path of the object rather than on the entire field of view.

²¹ (n.d.). Command Line Options. http://ds9.si.edu/doc/ref/command.html

²² (n.d.). Regions. http://ds9.si.edu/doc/ref/region.html





Trajectory indicators: start (green) and end (red).

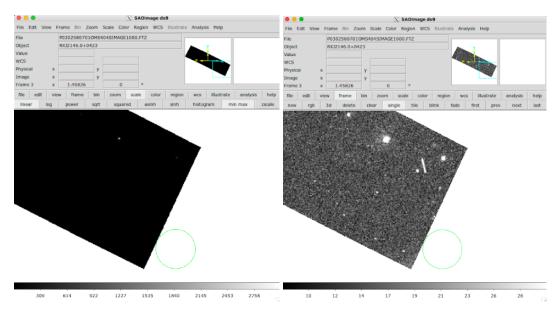
The start and end trajectory indicators are built from the ESASky SSOSS catalogue of potential serendipitous observations.

5.2.2.2 Adjusting DS9 scale

DS9 provides means to modify its default display settings by means of its "scale" menu²³. As per recommendation from the Thesis Director, the "zscale" command is used as it provides very good contrast to ease the object's detection.

²³ (n.d.). DS9 Scale Menu. http://spiff.rit.edu/tass/ds9/mscale.html





DS9 linear scale (left) vs zscale (right).

5.2.3 Recording the analysis outcome

Once the user has analysed the data, the software collects their input.

User input interface.

A standard input/output (I/O) implementation is used to gather the user's input. Said input is mostly limited to a shortlist of options:



- DETECTED (Y) Indicating that the object is distinctively

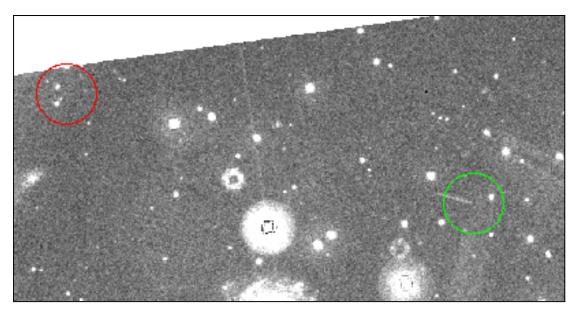
observable in the image.

- DUBIOUS (D) Used for objects whose presence is not clearly

identifiable nor outruled.

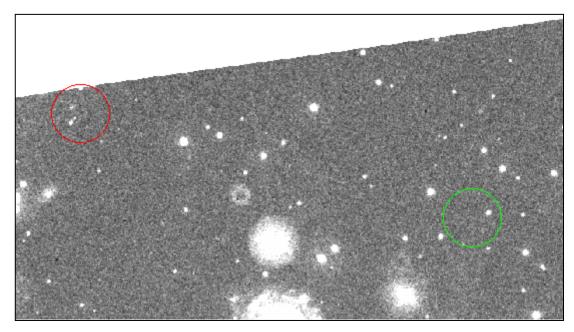
NOT_DETECTED (N) Indicating that there is no indication of the object

being present in the image.



An example of a clear detection (observation 0692330401 - Ivanka - L filter).





An example of a "dubious" detection (observation 0692330401 - Ivanka - U filter).

After each observation, the analysis outcome is recorded.

```
class Recorder:
    """Analysis output recorder interface."""

def prepare_observation_record(self, observation: observation.Observation):
    """Prepares the next observation record.

Args:
    observation (observation.Observation): the observation instance
    """
    pass

def record_filter_input(self, filter: str, input: input.Input):
    """Records the specified input for a specified filter.

Args:
    filter (str): the filter (e.g. 'U')
    input (input.Input): the analysis input
    """
    pass

def record_observation(self):
    """Records the current observation.

Args:
    filters (List[str]): list of filters that have been considered.
    """
    pass
```

Analysis output recorder.

An implementation writing the analysis output to a comma-separated value file (CSV) was used.



```
observation,object,S,M,L,U,B,V

0012440101,Lictoria,,,D,,D,

0081340801,Stepanov,,,N,N,D,

0106660601,1994 UF2,,,N,N,,

0110980101,Lucubratio,,,Y,,Y,

0110980601,1030 T-1,,,N,N,Y,

0111170101,Velichko,,,N,,,N
```

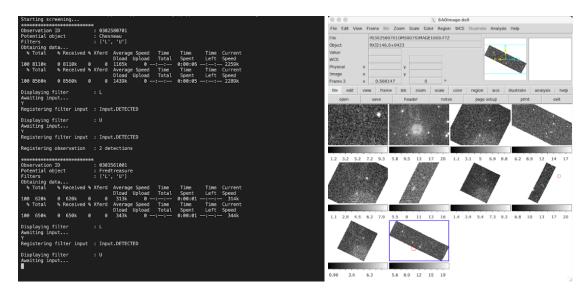
Sample of the CSV output file recorded during the process.

The output file can be imported as a table into other analysis tools. Below, the same output, in a table format:

N	observation	object	S	М	L	U	В	٧
1	12440101	Lictoria			D		D	
2	81340801	Stepanov			N	N	D	
3	106660601	1994 UF2			N	N		
4	110980101	Lucubratio			Υ		Υ	
5	110980601	1030 T-1			N	N	Υ	
6	111170101	Velichko			N			N

A subset of the screening results. The full table can be found in the Annexes section.





Screenshots of what the screening process looks like for the user.

5.3 Photometry

This section describes the work and process used to determine the magnitude(s) of the selected objects from the previously described screening process. A piece of Python code, leveraging the popular astronomy library Astropy²⁴, is written to carry out the following flow:

²⁴ (n.d.). Astropy. https://www.astropy.org/



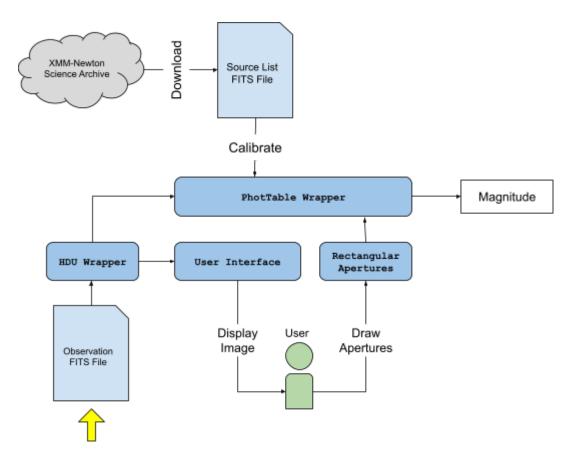


Diagram of the photometric process.

- 1. The process starts specifying the location of the observation FITS file, which is injected into an HDU^{25 26} (Header Data Unit) Wrapper instance.
- 2. A PhotTable Wrapper instance (an Astropy's QTable²⁷ utility wrapper) is created and fed with said *HDU Wrapper*. One can then:
 - a. Download the corresponding "source list" (details of this specific product can be found in the following sections) FITS file from XMM-Newton Science Archive and
 - b. obtain the coefficients of the linear model to be used to calibrate the actual observation file.

https://docs.astropy.org/en/stable/api/astropy.table.QTable.html#astropy.table.QTable

²⁵ FITS Primer. (2014, October 28). NASA FITS. https://fits.gsfc.nasa.gov/fits_primer.html

²⁶ Header Data Unit — Astropy v5.2.1. (n.d.). Astropy.

https://docs.astropy.org/en/stable/io/fits/api/hdus.html

²⁷ QTable — Astropy v5.2.1. (n.d.). Astropy.



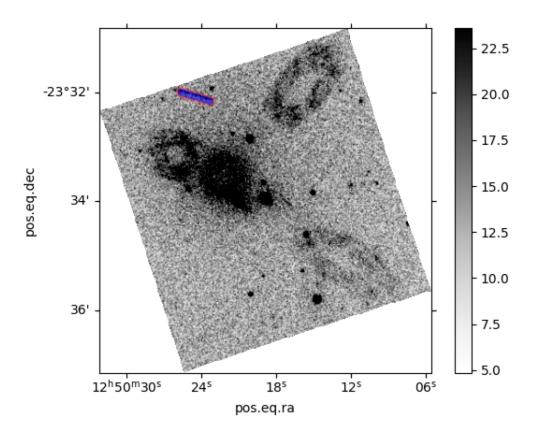
- 3. A *User Interface* instance is created and launched, allowing the user to select the trail in the image. The user's input selection is translated into the two *Rectangular Aperture* instances.
- 4. The calibrated linear model of the *PhotTable Wrapper* is used together with the *Rectangular Apertures* to calculate the calibrated magnitude of the object.

5.3.1 Rectangular aperture (trail) photometry

Given the nature of the object trail, rectangular aperture photometry was used instead of the most commonly known circular aperture photometry. Two concentric and aligned rectangles are used to determine the object's magnitude.

Just like in standard circular photometry, where two concentric circles are used, the outer rectangle is used to subtract the background *noise*. In order to determine said rectangles, the user is presented with the observation image for them to select the edges of the trail. The two rectangles are then defined around the selected points.





User interface to define rectangular apertures (outer rectangle in red, inner rectangle in blue).

5.3.2 Calibration against source list

In order to calibrate the observation images, we make use of the "source list" files (*SRCLIST* in XMM-Newton terminology) provided by the XMM-Newton mission. The header of this file contains the "zero-points and conversion factors and quantities derived during the astrometric rectification of the field against the USNO-B1 catalogue" (reference to the page 29 of XMM-Newton Individual Specifications).d

These parameters are then leveraged to perform calibration of the object's computed aperture photometry using the following expression:

$$m_{cal} = ABF0_i \cdot m_{ape} + ABM0_i$$

Where:



 $m_{\it cal}$ is the calibrated magnitude.

 $m_{\rm ape}$ is the magnitude measured via aperture photometry.

 $\mathit{ABF0}_{i} \ \ \textit{is the conversion slope for filter 'i'}.$

 $\mathit{ABM0}_i \;\; \textit{is the conversion zero} \; - \; \textit{point for filter'i'}.$



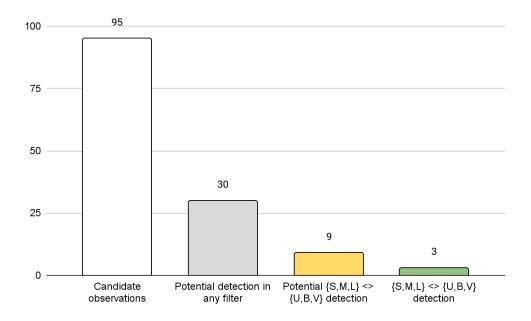
6 Results & analysis

This section breaks down in deeper detail the results obtained from each one of the steps described in the methodology section. It also includes a section outlining potential future work and improvements.

6.1 Screening

After completing the screening of all 95 candidate observations...

- ...there are **30** observations where the object might have been detected (i.e. "dubious" or "clear" detection) in one or more of either the {S,M,L} filters or the {U,B,V} filters (i.e. not UV/optical overlap)...
- ...out of which there are **9** observations where the object might have been detected (i.e. "dubious" or "clear" detection) in one or more of the {S,M,L} filters as well as in one or more of the {U,B,V} filters...
- ...out of which there are **3** observations the object has been detected (i.e. "clear" detection) in one or more of the {S,M,L} filters as well as in one or more of the {U,B,V} filters.



Observations breakdown after the screening process.



The 3 observations where there the object has been detected in both one or more {S,M,L} filters and one or more {U,B,V} filters are:

N	observation	object
4	110980101	Lucubratio
25	302580701	Chesneau
26	303561001	Fredtreasure

S	М	L
		х
		Х
		Х

U	В	٧
	Х	
Х		
Х		

Observations showing one or more clear detections in both {S,M,L} and {U,B,V} filters.

The actual images of the 3 above-mentioned objects can be found in the Annexes section.

6.2 Photometry

The 3 observations where detections in both UV {S,M,L} and optical {U,B,V} filters exist are photometrically analysed using the process described in the Methodology section. The following magnitude figures are obtained:

This is to be FIXED

N	observation	object
4		
	110980101	Lucubratio
25	302580701	Chesneau
26	303561001	Fredtreasure

S	М	L
		{18.5662, 18.5662}
		18.5662
		18.5662

	U	В	٧
		19.0809	
ſ	19.189		
ſ	19.189		

Computed magnitudes for the 3 observations showing one or more clear detections in both {S,M,L} and {U,B,V} filters.

6.3 Future work and improvements

Several improvements and potential future lines of work are discussed below:

- Image-trajectory overlap: currently all images of a possible observation are displayed during the screening process. In the best case scenario, there is only one, while in the worst case scenario there might be up to 30 images. Many of these images footprint does not overlap with the actual trajectory of the object, thus



displaying many images for analysis where the chance of detecting the object is virtually impossible. This is quickly ruled out by the user thanks to the trajectory indicators, but one could optimise the process further by ruling them out programmatically before even presenting them for screening.

- Full **automation**: at the moment, the figure of a user is necessary ("human in the loop"), however, one could include a trail detection algorithm and fully automate both the screening and the photometric process.
- Re-running against an **updated catalogue** version: the present work is based on the ESASky SSOSS catalogue published towards the end of 2021, where all the starting 985 potential observations were made available. One could re-run the whole cross-matching process and provide another list of observations to analyse.
- Remove **DS9 dependency**: whilst DS9 is a powerful tool, it currently offers a few limitations when it comes to its programmatic usage. One could utilise a Python library for the display of FITS files. The current software pattern would allow for the implementation and easy "plug-in" of a Python-based FITS interface.



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TO BE UPDATED BEFORE SUBMISSION

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8 Annexes

8.1 Candidate observations

The following table outlines all 95 potential XMM-Newton serendipitous observations of interest, where:

- N is the row ordinal.
- observation is the observation ID (as per XMM-Newton's Science Archive).
- sso_name is the potential Solar System Object name in the XMM-Newton OM FoV.
- {ra1, dec1} is the SSO's right ascension and declination at the start of the observation.
- {ra2, dec2} is the SSO's right ascension and declination at the end of the observation.
- *filters* indicates the potential filters used during the observation.

N	observation	sso_name	ra1	dec1	ra2	dec2	filters
1	0012440101	Lictoria	13.99603658	-1.415317889	14.07883767	-1.363111917	L;B
2	0081340801	Stepanov	183.3527003	2.7053835	183.433249	2.687358	L;U;B
3	0106660601	1994 UF2	333.6775958	-17.72910939	333.9756773	-17.53652372	L;U
4	0110980101	Lucubratio	170.061614	13.66864472	170.2531624	13.58085442	L;B
5	0110980601	1030 T-1	199.8925842	-14.85586353	200.1011217	-14.91287867	L;U;B
6	0111170101	Velichko	98.05291688	17.67519933	98.37874979	17.70504883	L;V
7	0137550501	Vermeer	83.65883033	21.96132228	83.72975342	21.95673122	L;U
8	0148090501	2000 VH57	268.6228585	-26.34105697	268.6597257	-26.33875756	L;B
9	0148560501	2000 OR6	157.6945887	5.506792639	157.9910666	5.444162528	L;V
10	0153450101	Coubertin	191.7900402	-5.714503389	192.0338537	-5.8043765	L;B
11	0153950901	2000 SG172	245.6509016	-15.71548278	245.687865	-15.72228931	L;U
12	0164570401	1998 QN30	229.0141158	-16.05640242	229.2929736	-16.14343586	L;U
13	0202680101	1992 AJ1	263.4018785	-26.09088186	263.940696	-26.11426953	L;U
14	0202680101	Puntel	263.1458409	-26.11714492	263.7103745	-26.16403192	L;U
15	0202730101	Kiyosato	155.414775	21.64732233	155.5115943	21.58226161	L;U;B
16	0203170301	1998 YB12	187.924908	0.3078198611	188.2312754	0.1890703333	L;U;B;V
17	0203450201	1941 UN	330.777767	-19.12108378	330.9844593	-19.069593	L;U
18	0203850201	1981 ET34	278.7704483	-7.654013611	278.8745769	-7.677327028	L;U
19	0206060101	1993 UB3	358.6213643	5.807185972	358.7399671	5.873919833	L;U



N	observation	sso_name	ra1	dec1	ra2	dec2	filters
20	0206060201	Vanavara	144.8699843	14.97476194	144.9659829	14.94839681	L;U
21	0206490301	Africa	337.1189521	-24.69079364	337.2161115	-24.68050169	L;U
22	0300240101	Mucha	139.650819	16.33086269	139.7237488	16.31634964	L;U;B
23	0300480301	1994 Y01	133.5344843	20.16909269	133.6593827	20.11736764	L;U;B;V
24	0300960631	Hermitage	204.3960185	-9.539437083	204.4068013	-9.540443056	L;B
25	0302580701	Chesneau	326.4374095	4.212535	326.5023323	4.446862	L;U
26	0303561001	Fredtreasure	192.5847993	-23.53889469	192.6238483	-23.529534	L;U
27	0312790101	1999 AD32	83.45220263	21.92756267	83.58099579	21.99086489	L;U
28	0402360101	2006 BQ6	27.57513963	32.19779597	20.13579171	33.51657169	M;L;U;B
29	0402430301	Masciarelli	266.332632	-28.93590631	266.5198225	-28.98743756	L;U
30	0402750301	Kazo	35.18939329	19.84358708	35.31994388	19.90695697	L;U
31	0500760101	1999 XN105	168.2132115	13.48386681	168.2961424	13.48310722	L;U
32	0501270301	The	98.40760025	17.72570306	98.44330771	17.72696461	L;U
33	0502091601	Kulibin	139.6860336	16.17447492	139.9306879	16.10896939	L;B
34	0502120101	Ibuki	184.5898656	5.767884056	185.0411175	5.664890611	L;U;V
35	0502430101	2000 BJ4	197.675828	-5.848601611	197.8108237	-5.93855275	L;U
36	0503490201	Naruke	340.5789013	-9.697185722	340.805813	-9.601553056	L;U
37	0503490201	2000 QP27	340.263912	-9.828102417	340.9032975	-9.58547225	L;U
38	0504780501	1999 XQ57	193.2852633	-9.254789083	193.5174435	-9.269204778	L;U
39	0552860101	Nantong	163.640493	-5.670915611	163.651515	-5.753722778	L;U
40	0556212301	Amenemhet	223.6749917	1.731918444	223.7060366	1.711334833	M;L;B
41	0601391001	Joan	311.1092784	-10.79975797	311.3062858	-10.78449478	S;M;L;U;B;V
42	0601670101	1986 RP5	19.7594455	3.550315778	19.94961175	3.669347333	M;L;U
43	0604740101	Lijiang	321.4909871	-12.20326347	321.776253	-12.12629567	M;L;U
44	0604740101	2000 NA6	321.2284947	-12.19873319	321.6523976	-12.00705717	M;L;U
45	0650510301	1999 SG12	23.21132146	30.93349644	23.55411408	31.11216489	M;L;U;B
46	0653840401	Grotius	24.86671587	6.247936944	24.93093133	6.264996833	S;M;L;U
47	0653950201	1993 SG1	82.50929946	10.55111419	82.71532771	10.47722242	L;U;B;V
48	0656200101	2000 WU93	137.2766764	14.62784539	137.3296748	14.61574197	M;L;U
49	0670120301	Chrisclark	343.5239665	-17.82484172	343.5560615	-17.647393	S;M;L;U;B;V
50	0670880401	1999 AN25	343.271595	11.46389467	343.5867534	11.57390897	S;M;L;U
51	0672990201	1994 CG2	318.0854782	-30.82999664	318.248346	-30.79596678	M;L;U
52	0673310101	2000 JZ79	186.3821592	13.11793753	186.443617	12.82925503	M;L;U
53	0673310101	2000 AV91	186.1031917	13.03456053	186.2139895	12.89814914	M;L;U
54	0673550201	1996 YP	265.897439	-29.70555036	266.1531568	-29.73510025	M;L;U
55	0674370201	Zurich	136.799451	14.87054631	137.150276	14.6254395	M;L;U
56	0674480401	Potomac	211.0622944	-1.794742861	211.0822733	-1.792068667	L;U



N	observation	sso_name	ra1	dec1	ra2	dec2	filters
57	0692330401	Ivanka	112.1893285	33.89455739	112.3496495	33.93021694	M;L;U
58	0692330501	1998 HF34	171.3479332	14.55508569	171.4278274	14.53439111	M;L;U
59	0692510201	Quaide	142.1817295	18.83117456	142.2683561	18.82097528	M;L;V
60	0693820201	2000 RX67	197.619011	-1.358278028	197.819275	-1.411782806	M;L;U
61	0694510101	Siegena	212.153216	-3.086574139	212.3203522	-3.078343194	M;L;U;B
62	0700182001	Landi	322.2720505	-7.793742944	322.3753971	-7.771863972	M;L;U
63	0721010501	1989 ST10	262.0557056	-14.185319	262.5758778	-14.32163672	S;M;L;U;B;V
64	0722310201	Auster	311.8667542	-10.03062875	312.1446029	-9.988439417	M;L;U
65	0723800701	1981 FT	181.0776443	1.763994861	181.4599945	1.556985611	S;M;L;U;B;V
66	0727771001	1988 XT1	329.8151669	-30.24738586	329.9649954	-30.22888356	S;M;L;B
67	0740920301	Tampere	189.9916692	-5.242599694	190.0440417	-5.266937222	S;L;U
68	0742570101	1990 QT9	130.4161485	19.43254819	130.512747	19.40390586	M;L;U
69	0743050301	2000 SL1	13.22112492	12.73247244	14.08068717	12.77018519	S;M;L;U;B;V
70	0743630501	2000 SG234	266.160831	-28.99608153	266.4460373	-29.01865606	M;L;U
71	0743950501	Aakashshah	146.3334294	10.01490692	146.5087875	9.944300806	S;M;L;B;V
72	0744420101	1988 RK	276.5005378	-12.98744389	277.1083537	-13.11541775	S;M;L;B
73	0744440301	Lipschutz	191.5872185	2.524155889	192.0992658	2.315665	S;M;L;U;V
74	0744440301	2001 FV5	191.3991292	2.555875667	191.8783471	2.321374083	S;M;L;U;V
75	0748190101	1999 WA3	28.89897346	5.562144528	29.00509067	5.689929778	M;L;U;B;V
76	0748391301	1998 EC9	266.4610222	-20.21344439	267.1787076	-20.26542956	S;M;L;U
77	0762520301	Boyan	135.95937	15.10115797	136.1865554	15.03699531	S;M;L;U;B;V
78	0763100101	Raissa	272.4010435	-26.10797106	272.7722155	-26.09434092	S;M;L;U
79	0763100101	Silentium	272.7717822	-26.24762669	273.2145032	-26.20041814	S;M;L;U
80	0782650101	1999 RU128	148.4771184	1.610909611	148.5702264	1.573129028	M;L;U
81	0793183501	Pluto	290.4538513	-21.19250028	290.4627145	-21.19216222	L;U;B;V
82	0793183801	Pluto	290.5976094	-21.20850228	290.5941724	-21.21058642	L;U;B;V
83	0800380101	Aimeemcarthy	334.2823285	-3.633520861	334.5500116	-3.628896917	M;L;U
84	0800400501	Sarpedon	137.5143637	-0.7671195	137.5362295	-0.744149	M;L;U
85	0800400601	2002 VU94	132.693046	-0.0530325	132.6390517	0.05990219444	M;L;U
86	0803161101	Asteropaios	159.304195	-2.555804833	159.3039392	-2.567429139	L;B
87	0803950801	Salazar	146.9090978	14.37213733	146.9327653	14.36387231	L;B
88	0803952201	Reseda	180.29188	1.151024972	180.3209618	1.136621639	L;B
89	0803952601	Joensuu	126.3411467	31.90827689	126.4194533	31.91556219	L;B
90	0804250301	Flagstaff	266.6556002	-29.83210128	266.7527539	-29.84931656	S;M;L;U;B
91	0810600201	2001 UY127	50.2470725	-1.158312056	50.30279604	-1.026853944	M;L;U
92	0811212701	1999 XT90	197.299954	-23.56913144	197.4071665	-23.70903806	M;L;U
93	0820460101	1999 FC32	177.9620883	3.972947472	178.0113729	3.942962222	L;V



N	observation	sso_name	ra1	dec1	ra2	dec2	filters
94	0821250601	2000 VR36	35.83477292	-3.512480722	36.04166496	-3.298254861	M;L;U
95	0830191001	2001 AG18	197.108645	-23.29220028	197.2994372	-23.30699	M;L;U



8.2 Screening results

The following table contains the screening results for all 95 potential XMM-Newton serendipitous observations of interest, where:

- *N* is the row ordinal.
- observation is the observation ID (as per XMM-Newton's Science Archive).
- object is the potential Solar System Object name in the XMM-Newton OM FoV.
- {S, M, L, U, B, V} is the screening result for a particular filter, where:
 - Y indicates a clear detection.
 - D indicates a dubious detection.
 - *N* indicates no detection.

Rows have been colour-coded, where:

The object has not been detected.
The object might have been detected in one or more filters but either in the {S,M,L} filters or in the {U,B,V} filters.
The object might have been detected (i.e. "dubious" or "clear" detection) in one or more of the {S,M,L} filters as well as in one or more of the {U,B,V} filters.
The object has been detected (i.e. "clear" detection) in one of the {S,M,L} filters as well as in one of the {U,B,V} filters.

N	observation	object	S	М	L	U	В	٧
1	12440101	Lictoria			D		D	
2	81340801	Stepanov			N	N	D	
3	106660601	1994 UF2			N	N		
4	110980101	Lucubratio			Υ		Υ	
5	110980601	1030 T-1			N	N	Υ	
6	111170101	Velichko			N			N
7	137550501	Vermeer			N	N		
8	148090501	2000 VH57			N		Υ	
9	148560501	2000 OR6			N			N
10	153450101	Coubertin			N		N	
11	153950901	2000 SG172			N	Υ		



N	observation	object
	164570401	1998 QN30
3	202680101	1992 AJ1
4	202680101	Puntel
15	202730101	Kiyosato
16	203170301	1998 YB12
17	203450201	1941 UN
18	203850201	1981 ET34
19	206060101	1993 UB3
20	206060201	Vanavara
21	206490301	Africa
22	300240101	Mucha
23	300480301	1994 Y01
24	300960631	Hermitage
25	302580701	Chesneau
26	303561001	Fredtreasure
27	312790101	1999 AD32
28	402360101	2006 BQ6
29	402430301	Masciarelli
30	402750301	Kazo
31	500760101	1999 XN105
32	501270301	The
33	502091601	Kulibin
34	502120101	Ibuki
35	502430101	2000 BJ4
36	503490201	Naruke
37	503490201	2000 QP27
38	504780501	1999 XQ57
39	552860101	Nantong
40	556212301	Amenemhet
41	601391001	Joan
42	601670101	1986 RP5
43	604740101	Lijiang
44	604740101	2000 NA6
45	650510301	1999 SG12
46	653840401	Grotius
47	653950201	1993 SG1
48	656200101	2000 WU93



N	observation	object
I	670120301	Chrisclark
	670880401	1999 AN25
	672990201	1994 CG2
2	673310101	2000 JZ79
53	673310101	2000 AV91
54	673550201	1996 YP
55	674370201	Zurich
56	674480401	Potomac
57	692330401	Ivanka
58	692330501	1998 HF34
59	692510201	Quaide
60	693820201	2000 RX67
61	694510101	Siegena
62	700182001	Landi
63	721010501	1989 ST10
64	722310201	Auster
65	723800701	1981 FT
66	727771001	1988 XT1
67	740920301	Tampere
68	742570101	1990 QT9
69	743050301	2000 SL1
70	743630501	2000 SG234
71	743950501	Aakashshah
72	744420101	1988 RK
73	744440301	Lipschutz
74	744440301	2001 FV5
75	748190101	1999 WA3
76	748391301	1998 EC9
77	762520301	Boyan
78	763100101	Raissa
79	763100101	Silentium
80	782650101	1999 RU128
81	793183501	Pluto
82	793183801	Pluto
83	800380101	Aimeemcarthy
84	800400501	Sarpedon
85	800400601	2002 VU94



N	observation	object	S	М	L	U	В	٧
86	803161101	Asteropaios			D		D	
87	803950801	Salazar			D		N	
88	803952201	Reseda			N		N	
89	803952601	Joensuu			N		N	
90	804250301	Flagstaff	N	N	N	N	Υ	
91	810600201	2001 UY127		N	N	Υ		
92	811212701	1999 XT90		N	N	N		
93	820460101	1999 FC32			N			N
94	821250601	2000 VR36		N	N	D		
95	830191001	2001 AG18		N	N	N		



8.3 Detection images

8.3.1 Obs. 11098010 - Lucubratio

8.3.1.1 L Filter

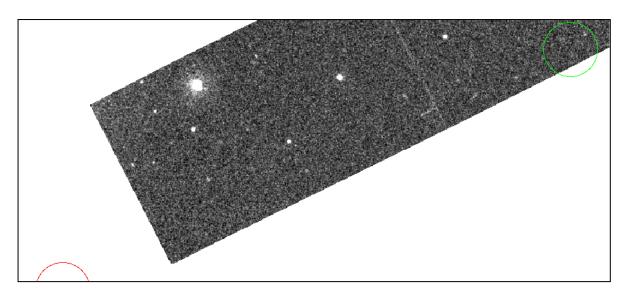


Image P0110980101OMS406SIMAGE1000

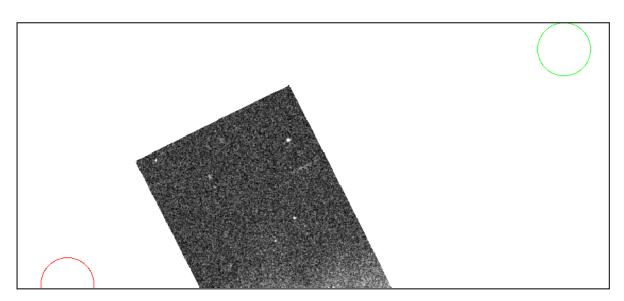


Image P01109801010MS411SIMAGE1000



8.3.1.2 B Filter

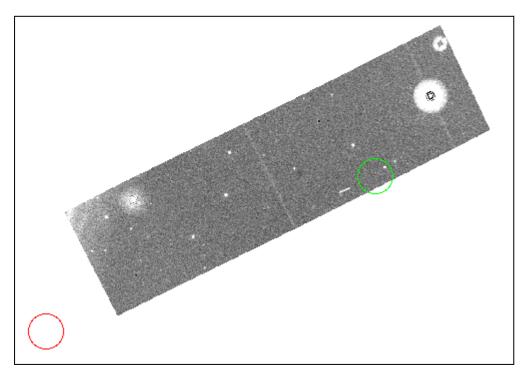


Image P01109801010MS402SIMAGE1000



8.3.2 Obs. 0302580701 - Chesneau

8.3.2.1 L Filter

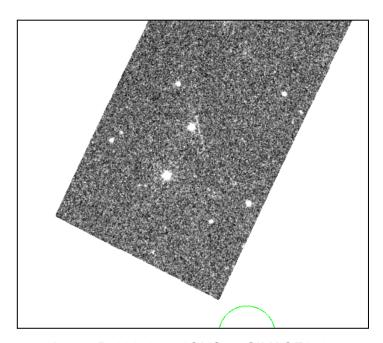


Image P0302580701OMS405SIMAGE1000

8.3.2.2 U Filter

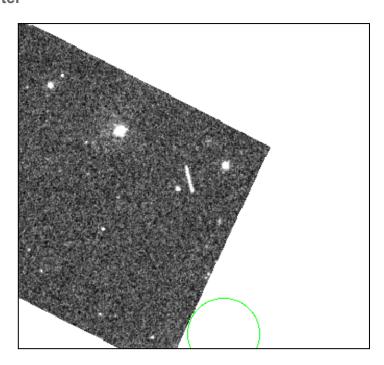




Image P0302580701OMS404SIMAGE1000

8.3.3 Obs. 0303561001 - Fredtreasure

8.3.3.1 L Filter

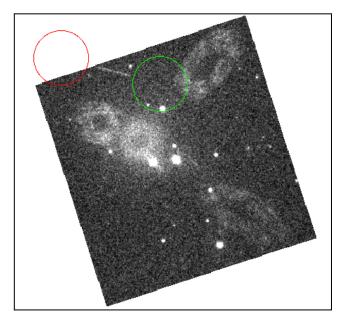


Image P0303561001OMS007SIMAGE0000

8.3.3.2 U Filter

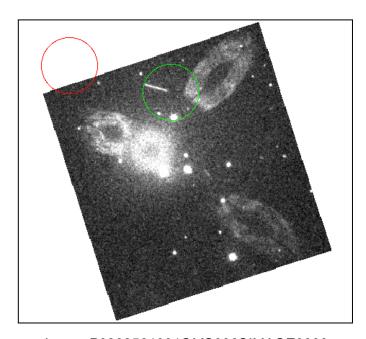


Image P0303561001OMS006SIMAGE0000

