IAC-22,D1,IP,15,x72679

The Arcanum Telescope: A space observation platform on the outer solar system

Jesus Galinzoga[a*], Christina Bornberg[a], James McKevitt[a], Tom Dixon[a], Franco Criscola[a], Alisa Zaripova[a], José E. Andino-Enríquez[a], Ramansh Sharma[a], Jack Kent[a], Jonathan J. Parkinson-Swift[a]

[a] *Conceptual Exploration Research, 71-75 Shelton Street, London, WC2H 9JQ, United Kingdom*
[*] Corresponding Author: hello@conexresearch.com

Abstract

Taking into consideration the wide-ranging science next generation launch vehicles will enable, the Arcanum mission is a proposed L-class spacecraft for the Neptunian system consisting of a Neptunian orbiter and a Triton lander and surface penetrators. This mission aims to answer several questions about Neptune, Triton and KBOs, as well as to constrain the known properties of exoplanets and cosmic dust. One of the orbiter's key instruments is the Arcanum Telescope; an off-axis three-mirror anastigmatic medium size instrument (0.5 m primary mirror) operating in the visible and near-infrared spectrum making observations from a highly-elliptic Neptunian orbit. Observations from such a vantage point are unique and invaluable to efforts of further understanding bodies beyond Neptune's orbit, mainly as they do not suffer from inner Solar System interference.

Keywords: Telescope, Kuiper Belt Objects, L-class, Neptune.

1. Introduction

We present the Arcanum Telescope and compare it with missions like the Hubble Space Telescope, Spitzer Space Telescope, James Webb Space Telescope, as well as concepts such as ZEBRA and EXZIT. After a short introduction of each telescope, we will present configuration, science objectives and methods, instruments, sensitivity, spectrum, cooling, and mass and power.

1.1. Arcanum Mission

The Arcanum mission is an L-class spacecraft mission concept to the Neptunian system, focusing on the observation of Neptune, its captured moon Triton, Kuiper Belt Objects (KBOs), as well as extra galactic background light (EBL) in the near infrared spectrum.

The mission is unique due to the telescope being positioned in the outer Solar System, escaping zodiac light (ZL), and therefore being able to constrain the near-infrared extragalactic background light, hence allow for a better understanding of the early universe. Furthermore, it will be the first spacecraft since Voyager 2 in 1989 to visit Neptune and the first mission to orbit an ice giant. Choosing Neptune over Uranus as a destination for this mission will also allow for landing on the moon Triton, a potentially captured Kuiper Belt Object.

The plethora of science questions which are present in the Neptunian System (see the Arcanum Science Traceability matrix [1]) are answerable by a mother-daughter spacecraft configuration. Central to the mission is the Somerville orbiter with a lightweight space telescope, and an attached soft-landing platform, Bingham. The Bingham lander, along with two penetrators will land on, and the latter impact Triton. The in-situ element is used to characterise the surface and subsurface environment of Triton.

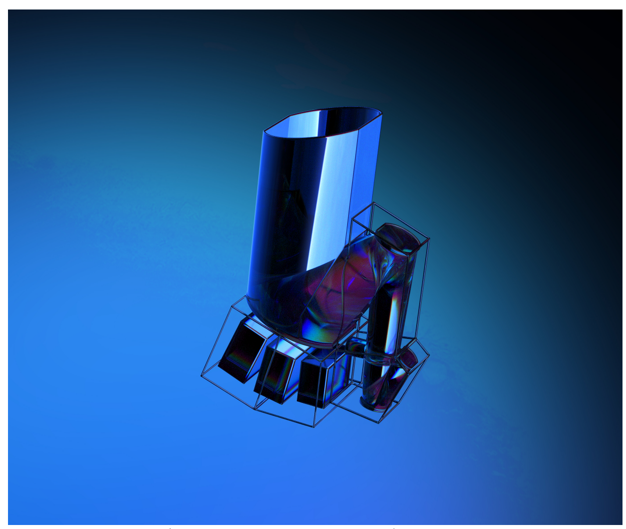

Figure 1. Arcanum Telescope

1.2. Arcanum Telescope

The Arcanum telescope is an off-axis three-mirror anastigmatic medium size instrument operating in the visible and near-infrared spectrum making observations from a highly-elliptic Neptunian orbit. It was introduced in previous work [2] [3] and in this work is further investigated.

2. Related Work

2.1. Hubble Space Telescope (HST)

The Hubble Space Telescope (HST) is a space telescope in Low Earth orbit (LEO). It launched in 1990 and remains in opearation.

Configuration: It is a Ritchey–Chrétien reflector telescope. **Instruments:** Advanced Camera for Surveys (ACS), Cosmic Origins Spectrograph (COS), Space Telescope Imaging Spectrograph (STIS: 0.115μm-1μm), Wide Field Camera 3 (WFC3: 0.2μm-1μm, 0.9μm-1.7μm), The Fine Guidance Sensors (FGS). **Spectrum:** The spectrum ranges from ultraviolat to NIR.

2.2. Spitzer Space Telescope

The Spitzer Space Telescope [4] was an infrared space telescope in Kepler's Earth Trailing Orbit. It was in operation between 2003 and 2020.

Configuration: It was a Ritchey–Chrétien telescope. **Instruments:** For observations, three instruments were used: Infrared Array Camera (IRAC), Infrared Spectograph (IRS), Multiband Imaging Photometer for Spitzer (MIPS). **Spectrum:** Infrared band (3.6-160μm). **Cooling:** The primary mirror was cooled to 5.5 K.

2.3. James Webb Space Telescope (JWST)

The James Webb Space Telescope (JWST) [5] is a space telescope on the Sun-Earth L2 Lagrange point, primarily designed for infrared observations.

Configuration: The type is a Korsch telescope. **Science Objectives and Methods:** The goal is to observe the first stars, formation of first galaxies and perform atmospheric characterisation of exoplanets. **Spectrum:** The bands range from orange to mid-infrared (0.6–28.3μm).

2.4. Zodiacal dust, Extragalactic Background and Reionization Apparatus (ZEBRA)

The zodiacal dust, Extragalactic Background and Reionization Apparatus (ZEBRA) [6, 7] is a concept currently under study for a telescope in the outer Solar System.

Configuration: They propose a three mirror off-axis telescope with multiple field and aperture stops. **Science Objectives and Methods:** The goal is to take measurements of the Extragalactic Background Light (EBL) without the dominant zodiacal light foreground. Additionally, the parallax between Saturn and Earth can be used for microlensing observations. **Instruments:** They propose the use of two commercial 2k x 2k IR detector arrays. The instruments are a 3 cm wide-field mapper and a 15 cm high-resolution imager. **Spectrum:** Visible to near-IR spectrum (0.4–5μm). **Mass and Power:** It has a minimal mass of 16.4 kg and a power requirement of 12.4 W. **Cooling:** This uses a passive cooling scheme to cool the optics and detectors to <50 K.

2.5. EXo-Zodiacal Infrared Telescope (EXZIT)

The EXo-Zodiacal Infrared Telescope [8] is the concept for a telescope around a Jovian Trojan asteroid at around 5.2 AU.

Configuration: They propose a 3-mirror reflective telescope to reduce thermal strain. **Science Objectives and Methods:** The goal is to achieve EBL observations with a drastically reduced ZL intensity. **Instruments:** They plan to use a $2k \times 2k$ array HgCdTe infrared detector. For spectroscopy, a Linear Variable Filter (LVF) is used to discriminate EBL from ZL. **Sensitivity:** The sensitivity (diffuse light) is defined as 1 $nWm^{-2}sr^{-1}$. A wide Field of View (FOV) is chosen to increase the visibility of the diffuse light. **Spectrum:** Visible to near-IR spectrum (0.4-1.6μm). **Cooling:** The telescope uses radiative cooling to 140 K to reduce dark current of the visible-IR detector. **Mass:** The combined mass of the aspherical mirrors is 1.225 kg.

3. Arcanum Telescope

The Arcanum Telescope (see Figure 1) is part of the Somerville orbiter, being in operation during its EEVEJN trajectory, as well as in the Neptunian system in a highly eccentric orbit. The distance to the Sun is approximately 30 AU from Neptune.

4. Configuration

Multiple telescope configurations were taken into account, however a instrument level design is proposed. In the first iteration, a two mirror Ritchey-Chrétien obscured design was considered, but later on changed to a three-mirror off-axis configuration with a 0.5 m aperature diameter.

4.1. Introduction of a three-mirror configuration

Three-mirror anastigmats (TMA) make it possible to minimise spherical aberration, coma, and astigmatism, hence enable wide fields of view on a more compact disposition of the main mirrors.

4.2. Simulations

The mirror disposition, radios and conic constant, as well as the spot diagram at the focal plane were obtained by Ray-trace simulations using a commercial software, see Figure 2. Many iterations were performed in order to obtain a focal plane behind the 0.5 m primary mirror.

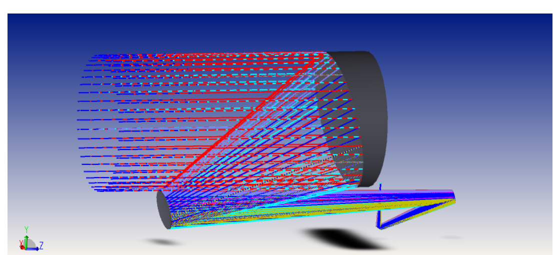

Figure 2. Simulation of a 3 mirror telescope.

Based on the focal length of the instrument and the effective aperture, an angular resolution of 0.35×0.5 arseconds is being considered. Nine objectives were simetrically distributed on the rectangular field of view to perform a preliminary evaluation of the focus capabilities of the current configuration. Figure 3 shows the resulting image surface spot diagram.

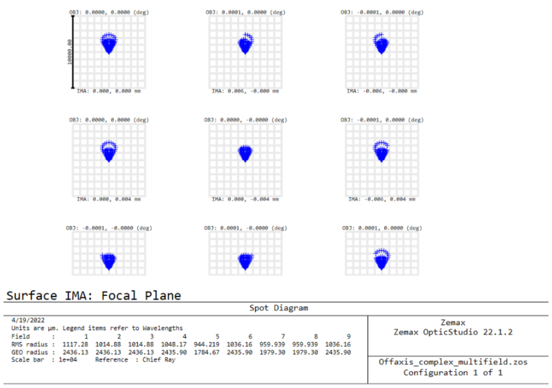

Figure 3. Image surface spot diagram of the focal plane.

5. Science Objectives and Methods

In this section, we will discuss the Remote (R) science objectives of the Arcanum mission [3], focusing on observations beyond the Neptunian system.

5.1. R-1. Kuiper Belt Formation

5.1.1. Key scientific questions

- What were initial stages, conditions and processes of Solar System formation?
- What is the reason for highly eccentric orbits of Kuiper Belt Objects?
- Is there evidence of a ninth Planet?
- How accurate are KBO positions?
- What is the composition of KBOs?

5.1.2. Planet 9

In the past decade nearly two-thirds of the known trans-Neptunian objects, including objects beyond 1000 AU, were discovered. Orbits of the most distant objects are highly eccentric, which is suggested to be due to the presence of a ninth planet. The planet is estimated to be several times more massive than Earth, while smaller than Neptune.

Previous work focuses on determining characteristics that a missing planet in the solar system might have:

- Period: 10,000 – 20,000 years [9]
- Semi-major Axis: 380^{+140}_{-80} (AU) [10]
- Perihelion: 300^{+85}_{-60} (AU) [10]
- Eccentricity: 0.2-0.5 [11]
- Inclination: $16 \pm 5°$ [10]
- Argument of Pericenter: 150° [12]
- Mean Anomaly: 0.5 [9]
- Mass: $6.2^{+2.2}_{-1.3}\ M_{Earth}$ [10]

5.1.3. Luminosity of Planet 9

One key criteria of the Arcanum Telescope, neccessary to address the scientific goals defined above, is that Planet Nine is resolved. This means that not only a sufficiently high angular resolution, but also radiometric sensitivity is required. Considering this from another perspective, it is also useful to quantify the increase in observed flux of Planet Nine when observed from Neptune as opposed to Earth.

Firstly, however, some context for this problem can be provided by comparing Planet Nine with Pluto when observed solely from Earth. Using a relationship for albedo, A, this difference in observed flux between Planet Nine and Pluto can be quantified. The albedo equation, showing the ratio of brightness of a star and a planet is as follows [13]:

$$\frac{F_p}{F_*} = A\left(\frac{R_p}{a}\right)^2, \tag{1}$$

where R_p is the planetary radius and a is the planet's orbital distance from the star. Equation 1 can be used to arrive at these quantified relationships between Pluto and Planet Nine, as observed from Earth [14]:

$$\delta_R \sim \left(\frac{R_9}{R_P}\right)^2 \left(\frac{a_9}{a_P}\right)^{-4} \sim 7.7 \times 10^{-3} \tag{2}$$

where δ_R is the ratio of reflected light fluxes.

$$\delta_E \sim \left(\frac{R_9}{R_P}\right)^2 \left(\frac{a_9}{a_P}\right)^{-2} \sim 0.7 \tag{3}$$

where δ_E is the ratio of thermal emission fluxes, assuming both bodies posess similar temperatures [15].

It is clear, therefore, that Planet Nine will be harder to observe than Pluto, and that in the thermal region it should appear more pronounced.

Moving now to the Arcanum Telescope; given the closer proximity of the instrument to Planet Nine, an associated brightness increase can be expected and quantified. The relationship for apparent brightness is:

$$b = \frac{L}{4\pi d^2} \tag{4}$$

where L is the luminosity of Planet Nine and d is the distance between Planet Nine and the Arcanum Telescope.

The lumonosity of Planet Nine is not known, but thankfully this is unnecessary as only ratios are required. Simplfying this equation, it can be shown that

$$\frac{b_E}{b_N} = \frac{{d_N}^2}{{d_E}^2} \quad (5)$$

where b_E and b_N are the brightness of Planet Nine when observed from Earth and Neptune respectively, and d_E and d_N are the distances from Earth to Planet Nine and Neptune (and the Arcanum Telescope) to Planet Nine respectively.

This relationship can be used to show that given no interference, an approximately 20% increase in observed flux can be expected when observing Planet Nine from Neptune. In reality, this number will be far higher when remembering that zodiacal light interference will be removed. This value of 20% is, therefore, not only a lower bound for apparent brightness increase, but also the critical indicator of zodiacal light interference with observations from Earth. Assuming that once at Neptune, the Arcanum Telescope is immune to zodiacal light interference, any increase in brightness above this 20% value can be immediately attributed to zodiacal light and help in addressing one of the main science goals of this instrument. Clearly this principal can be applied to other objects outside of the region of zodiacal light interference, for example Pluto, before Planet Nine is located, if this occurs.

5.1.4. *Kuiper Belt Objects*

Since the discovery of the Kuiper Belt, telescopes have been improved decade over decade, finding thousands of bodies.

Here arises the main question: Why are KBOs important? And why should we perform research about them?

Formation:

In the early Solar System stage, the Kuiper Belt Objects were displaced to the outer part, ridding them from the catastrophic process that happened in the inner part. Thus, these bodies contain elementary information about this stage. Researching and analyzing the KBOs will give a significant advance in the understanding of the Solar System's origin and evolution.

Computer simulation models have been proposed to explain the formation of the Kuiper Belt. Based on the gravitational interactions of the Solar System's formative period, these models indicate that the Kuiper belt could have formed further into the Solar System and been displaced to its current position by interactions with Uranus and Neptune, and these, caused by turn by the gravitational influence of Jupiter [16].

With a minimum formation time of 4 My after the Solar System originated, the Kuiper Belt started to form. Since then, it is been suggested that it has maintained a homogeneous composition and also it is a rock-rich reservoir [17].

Composition:

Given the long distance between the telescopes (on Earth and those located in space), knowing and understanding the composition of the KBO have been a complete challenge [18]. Brown defined the early 2000s as a blossoming in the understanding of the KBOs' composition and their process. Nowadays, the surface composition, atmospheric loss, effects of giant impacts, and more KBOs' processes have been analyzed [18]. Starting from the biggest objects of the Kuiper Belt, Makemake, Eris, and Haumea are composed of ices (methane, ammonia, water, and carbon monoxide, among others) [19, 20, 21, 22]. In the same way, these KBOs could present geological activity [23, 21]. The average temperature oscillates between $35-50\,K$. Besides, Makemake and Eris could have an ice and rocks core [24], meanwhile Haumea could present hydrated silicates [25]. To better understand these similarities and differences between the KBOs is recommended to use several techniques. These techniques are remote sensing and comparison, collecting and analyzing atmospheric particles, Triton's surface temperature and thermal conductivity, and taking pictures while descending to see the catastrophic collisions.

5.1.5. *Method*

A telescope at around 30 AU enables the observation of KBOs with both, a shorter distance than from Earth, as well as reduced zodiac light.

5.2. *R-2. Constrain exoplanets*

5.2.1. *Key scientific questions*

- How do exoplanets influence a star with microlensing events?

5.2.2. *Microlensing observations*

In order to estimate the planetary mass of exoplanets and the separation of the planet to its host star from microlensing observations, information on the Einstein radius and the distance of the lens to the observer needs to be known. To calculate this distance, simple triangulation from parallax measurements is used [26] following the fact that an object that is observed from two different locations appears at different angular positions with respect to the background.

Traditionally, parallax is calculated by two measurements from Earth (annual parallax) that are six months apart [26], this is rather inconvenient for microlensing events that approximately last between several days and one month [27]. Another option is the contemporaneous observation, where two or more distant observatories (space or terrestrial parallax) look at the same microlensing event [28].

5.2.3. *Method*

Contemporaneous observation between the Arcanum telescope and a telescope on Earth or in Earth's orbit.

5.3. R-3. Cosmic Dust:

5.3.1. Key scientific questions

- How accurate are zodiacal dust models?

- To what degree does the zodiacal light region interfere with measurements of extragalactic background light (EBL)?

5.3.2. Infrared Radiation

About half of the energy our Sun emits is in the infrared spectrum. Its radiation heats up surrounding planets. In addition, Jupiter, Saturn and Neptune have their own internal heat source.

Zodiacal emission, which are thermal emissions of dust particles are in the near and mid-infrared spectrum [29]. Thermal emissions of small asteroids in the solar system are in the near and mid-infrared spectrum. Galactic cirrus emissions are in the far infrared spectrum. Faint galactic stars are in the near-infrared spectrum. The cosmic microwave background is in the long infrared spectrum.

5.3.3. Zodiacal light

Zodiacal light appears due to the glow of our own Sun and the hazy zodiacal glow from dust of the asteroid belt and hinder observations of the early Universe [6].

Especially the near-infrared (NIR) spectrum (0.75–1.4 µm) is of great importance, as background light from the first stars are expected to peak in this spectrum and would allow us to get information on the brightness and duration of the epoch of when the first stars were forming.

Modelling and removing zodiacal light remains a challenge for Extra Galactic Background light (EBL) measurements around 1 µm (infrared spectrum) but could be resolved by travelling to an orbit outside the asteriod belt. Compared to Earth, zodiacal light is 30 times fainter around Jupiter and 100 times fainter around Saturn [7].

5.3.4. Method

Use the telescope at several distances from the Sun while transfering to Neptune, including near Venus (closest to Sun), close to Earth, beyond the Asteroid belt and in the Neptunian orbit.

Due to the radiation from celestial bodies that would interfer with the optics and CCD cameras, observations while passing planets/moons are to be avoided.

5.4. R-4. Verification with telescope

5.4.1. Key scientific questions

- How accurate are spectrometers and cameras based on and around Earth observing exoplanets?

- How different are current Earth models when compared to remote sensing the Earth from Neptune?

5.4.2. Doppler spectroscopy

Doppler spectroscopy [30], also known as the radial-velocity method or ”the Wobble Method” is an indirect method for finding exoplanets, where slight ”wobbling” of the host star occurs due to the gravitational influence of large bodies like planets.

5.4.3. Method

Mimic exoplanet observations using the distance between Neptune and Earth. By measuring the magnitude of the Sun’s ”wobble”, which we know from previous studies, we can determine how accurate our exoplanet detection techniques are.

5.5. R-5. Mapping of Triton for landing site selection

5.5.1. Key scientific questions

- Which three landmarks are most interesting on Triton and should be selected as landing sites for Bingham and the penetrators?

5.5.2. Method

In order to make decisions for landing sites of the Triton lander and penetrators, new image data of Triton is needed. On the transfer to Neptune, the telescope should capture images of Triton.

6. Instruments

Three instruments share the optics, a specialised spectograph, a surveys camera and a NIR camera, as shown in Figure 4. All instruments will be located behind the primary mirror, on an integrated module also containing the filter wheels. For the focal plane a 50×50 mm sensor was considered with a 12μm pixel size. The peak data rate is 2 Gbit per orbit (20 hrs), with an average data rate around 30 kbps.

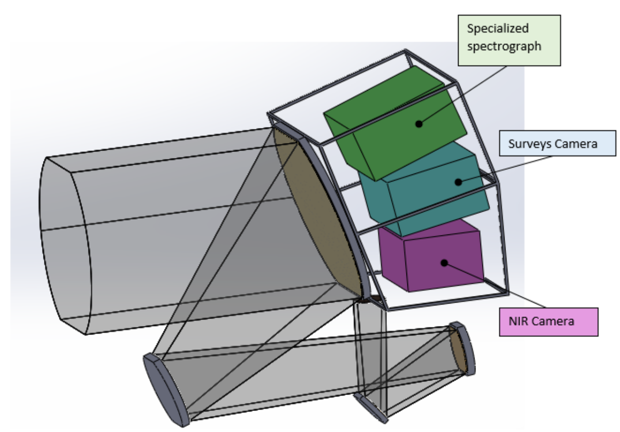

Figure 4. Instruments in the Arcanum telescope

7. Sensitivity

The sensitivity (diffuse light) is 1 $nWm^{-2}sr^{-1}$. This number is subject to change.

8. Spectrum

Due to the aim of designing a light and compact telescope, we chose a range between 0.1 and 1.5 μm.

Going further on the mid-IR would imply the need of a cryogenic system to cool down mirrors and instruments.

9. Cooling

In order to cool both optics and detectors of the Arcanum telescope, a passive cooling scheme is proposed. We decided against a cryogenic cooling scheme, since it is not needed given the small dimensions of the telescope, observations only between the UV and NIR spectrum as well as the already low temperatures in the Neptunian system. Considering the wavelength and intensity range, the temperature of the instrument need be no less than 100 K, but can be as high as 150 K.

10. Mass and Power

10.1. Mirror mass calculation

The mass of each of the three mirrors (M1, M2 and M3) and the folding mirror (FM) was calculated with the areal density for an open back beryllium mirror (30 kg m^{-2}), according to the reference [31].

- M1: 0.10704343m^2 $\Rightarrow$ 3.2113029 kg
- M2: 0.01668008m^2 $\Rightarrow$ 0.5004024 kg
- M3: 0.00741387m^2 $\Rightarrow$ 0.2224161 kg
- FM: 0.00409634m^2 $\Rightarrow$ 0.1228902 kg

The mass of all mirrors is **4.0570116 kg**.

10.2. Total mass

Including the structure and instruments, the total mass is calculated as 25 kg with a maximum of 30 kg to fit the mass budget of the scientific payload of the Somerville orbiter.

10.3. Power consumption

Considering three instruments a max power consumption of 15 W is estimated.

11. Conclusion

The telescope as part of the Arcanum Mission has a three-mirror configuration in the UV, visible and NIR spectrum.

We defined five main scientific objectives, including (1) observing Kuiper Belt objects (KBOs) and potentially proving the existance of a ninth Planet (2) observe exoplanets with micro-lensing events using the parallax between Earth and Neptune (3) image the extra galactic background light at multiple distances from Earth to understand the zodiacal dust and (4) observe Earth in front of the sun with the techniques of Doppler spectroscopy (5) observe Triton during the transfer to Neptune.

11.1. Future work

A list of considerations that should be looked into in future work include:

- Are planets such as Jupiter (while flyby) and Neptune (while in orbit) negatively affecting infrared measurements due to their reflection as well as internal heat source?
- By estimating/simulating the strength of zodiacal light in a Neptunian orbit, how much clearer can we expect to see KBOs like Planet 9 compared to a telescope at/around Earth.
- How close do we need to approach Triton in order to take images for landing site selection with the telescope?

Acknowledgements

The Conex Research team is an inspirational group of individuals from around the world. This work could not have been completed without all of them.

References

[1] Sophie Bulla et al. “A technical guide to the Arcanum Mission: a multirole Neptunian mission”. In: International Astronautical Congress 2022 (Paris, France, Sept. 18–22, 2022). 2022.

[2] James McKevitt et al. “An L-class Multirole Observatory and Science Platform for Neptune”. In: *arXiv preprint arXiv:2106.09409* (2021).

[3] James McKevitt et al. “The Arcanum Mission: Scientific Objectives and Instruments for Neptune, Triton and KBOs”. In: *Journal of the British Interplanetary Society* (2021), pp. 22–35.

[4] GG Fazio et al. “The infrared array camera (IRAC) for the spitzer space telescope”. In: *The Astrophysical Journal Supplement Series* 154.1 (2004), p. 10.

[5] Jonathan P Gardner et al. “The james webb space telescope”. In: *Space Science Reviews* 123.4 (2006), pp. 485–606.

[6] Asantha Cooray. “Extragalactic background light measurements and applications”. In: *Royal Society Open Science* (2016).

[7] James Bock et al. “Astronomical opportunities from the outer solar system”. In: *SPIE Newsroom* (2012).

[8] Kei Sano et al. “Development of EXo-Zodiacal Infrared Telescope (EXZIT) for observation of visible and near-infrared extragalactic background light”. In: *Space Telescopes and Instrumentation 2020: Optical, Infrared, and Millimeter Wave*. Vol. 11443. SPIE. 2020, pp. 979–995.

[9] NASA. *Universe Sandbox*.

[10] Michael E Brown and Konstantin Batygin. "The Orbit of Planet Nine". eng. In: *The Astronomical journal* 162.5 (2021), pp. 219–. ISSN: 0004-6256.

[11] Konstantin Batygin et al. "The planet nine hypothesis". eng. In: *Physics reports* 805 (2019), pp. 1–53. ISSN: 0370-1573.

[12] Konstantin Batygin and Michael E. Brown. "EVIDENCE FOR A DISTANT GIANT PLANET IN THE SOLAR SYSTEM". In: *The Astronomical Journal* 151.2 (Jan. 2016), p. 22. ISSN: 1538-3881. DOI: 10.3847/0004-6256/151/2/22. URL: http://dx.doi.org/10.3847/0004-6256/151/2/22.

[13] Renyu Hu. "Information in the Reflected-light Spectra of Widely Separated Giant Exoplanets". eng. In: *The Astrophysical journal* 887.2 (2019), pp. 166–. ISSN: 0004-637X.

[14] Adam Hibberd, Manasvi Lingam, and Andreas M Hein. "Can We Fly to Planet 9?" eng. In: (2022).

[15] Esther F. Linder and Christoph Mordasini. "Evolution and magnitudes of candidate Planet Nine". eng. In: *Astronomy and astrophysics (Berlin)* 589 (2016), A134–. ISSN: 0004-6361.

[16] Harold F Levison et al. "Origin of the structure of the Kuiper belt during a dynamical instability in the orbits of Uranus and Neptune". In: *Icarus* 196.1 (2008), pp. 258–273.

[17] CJ Bierson and F Nimmo. "Using the density of Kuiper belt objects to constrain their composition and formation history". In: *Icarus* 326 (2019), pp. 10–17.

[18] Michael E Brown. "The compositions of Kuiper belt objects". In: *Annual Review of Earth and Planetary Sciences* 40 (2012), pp. 467–494.

[19] ME Brown et al. "Methane and ethane on the bright Kuiper belt object 2005 FY9". In: *The Astronomical Journal* 133.1 (2006), p. 284.

[20] C Dumas et al. "Surface composition of the largest dwarf planet 136199 Eris (2003 UB)". In: *Astronomy & Astrophysics* 471.1 (2007), pp. 331–334.

[21] Adam Masters et al. "Neptune and Triton: Essential pieces of the Solar System puzzle". In: *Planetary and Space Science* 104 (2014), pp. 108–121.

[22] N Pinilla-Alonso et al. "The surface of (136108) Haumea (2003 EL61), the largest carbon-depleted object in the trans-Neptunian belt". In: *Astronomy & Astrophysics* 496.2 (2009), pp. 547–556.

[23] Marc Neveu et al. "Prerequisites for explosive cryovolcanism on dwarf planet-class Kuiper belt objects". In: *Icarus* 246 (2015), pp. 48–64.

[24] JL Ortiz et al. "Albedo and atmospheric constraints of dwarf planet Makemake from a stellar occultation". In: *Nature* 491.7425 (2012), pp. 566–569.

[25] ET Dunham, SJ Desch, and L Probst. "Haumea's shape, composition, and internal structure". In: *The Astrophysical Journal* 877.1 (2019), p. 41.

[26] Jennifer C Yee et al. "Criteria for sample selection to maximize planet sensitivity and yield from space-based microlens parallax surveys". In: *The Astrophysical journal* 810.2 (2015). ISSN: 0004-637X.

[27] Hyoun-Woo Kim et al. "KMT-2019-BLG-2073: Fourth Free-floating Planet Candidate with θ E < 10 μas". eng. In: *The Astronomical journal* 162.1 (2021), pp. 15–. ISSN: 0004-6256.

[28] E Bachelet, T. C Hinse, and R Street. "Measuring the Microlensing Parallax from Various Space Observatories". eng. In: *The Astronomical journal* 155.5 (2018), pp. 191–. ISSN: 0004-6256.

[29] WT Reach et al. "Mid-Infrared spectrum of the zodiacal light." In: *Astronomy and astrophysics* 315 (1996), pp. L381–L384.

[30] Michel Mayor, Christophe Lovis, and Nuno C Santos. "Doppler spectroscopy as a path to the detection of Earth-like planets". In: *Nature* 513.7518 (2014), pp. 328–335.

[31] H. Philip Stahl. *Lightweight optics: optical to ir*. 2016.