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Cover Page Footnote

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ABSTRACT

Fermi National Accelerator Laboratory is sending a 3U CubeSat into Low Earth Orbit (LEO) to search for a 3.5 keV photon corresponding to the decay of a theorized dark matter particle called the sterile neutrino. The CubeSat will encounter environmental variations while in orbit that can be computed through an orbital analysis using System's Tool Kit. In order to minimize thermal noise readout, improve optical resolution, and increase bandwidth, the sensors must be kept below 170 K while taking data. This temperature is difficult to achieve due to radiation from the Sun and the Earth's albedo radiation. Through the thermal analysis, the lowest temperature achieved by the CubeSat throughout its orbit was determined to be 190 K. In order to maintain the required sensor temperature, the CubeSat's cooling methods must be changed.

Using the information gained from the thermal analysis, the solar panel simulation results were analyzed. A six-panel approach resulted in maximum power of 11 watts. A nine-panel approach generated 22 watts at a sustained level, such that each orbit would yield a total of 39.6 kJ. With a power requirement of 20 watts, it was determined that the nine-panel approach would be ideal.

INTRODUCTION

The search for dark matter

Dark matter and dark energy are predicted to make up about 95% of all the matter in our universe. In order to explain the observed rotational curves of our galaxy, the theory of gravity predicts that dark matter must be dispersed evenly throughout our galaxy. The term dark matter was coined in the early 1930s by Swiss astronomer Fritz Zwicky [1]. Using redshift, Zwicky attempted to estimate the total mass and the velocities of visible matter in the Coma Cluster, one of the main clusters of galaxies in the Coma Supercluster. Through his calculations, he realized relative speeds of galaxies in the Coma cluster are too great to be held together by the gravity alone. He theorized that there must be additional unseen matter holding it together and named that unknown material 'Dunkle Materie' [1]. Dark Matter has become the subject of study for many physicists in order to better understand what makes up the universe. Each of the theorized dark matter candidates have yet to be supported by evidence. One candidate that is currently receiving a lot of attention in the scientific community is the sterile neutrino.

Neutrinos are leptons in the standard model of subatomic particles. Neutrinos interact solely via the weak interaction, which makes them particularly difficult to detect. As such, neutrinos have only been detected indirectly up to this point. The neutrinos that have been indirectly detected are nearly massless, which means they are able to achieve high speeds and energy. There are currently three flavors of neutrinos in the standard model that have been detected. Each corresponds with a charged partner: electron, muon, and tau [2]. A fourth neutrino flavor has been theorized and given the name sterile neutrino. This flavor of neutrino has not been detected and seems to interact independently of the fundamental forces that govern our universe, apart from gravity.

There are many different theories as to how a sterile neutrino could behave. One theory assumes the sterile neutrino is massive rather than close to massless. As the 7 keV mass sterile neutrino decays, its mass is converted into energy that occurs as a lighter state neutrino and a photon each with half of the converted energy [3]. Both lighter state neutrinos and photons are essentially massless, indicating the remainder of the mass is converted into kinetic energy.

The decay of sterile neutrinos may have been observed by large effective area telescopes such as Chandra, Suzaku and XMM-Newton. These telescopes have vast databases that have resulted in the detection of an unidentified emission line in far off galaxy clusters [4]. The 3.5 keV emission line detected is pictured in **Figures 1 and 2.** It corresponds with the theorized keV energy photon that is released from the decay of the sterile neutrino. If these X-Ray emission lines are indeed indirectly detecting sterile neutrino decay, a prime candidate for dark matter, then this same emission line should be present in our own galaxy.

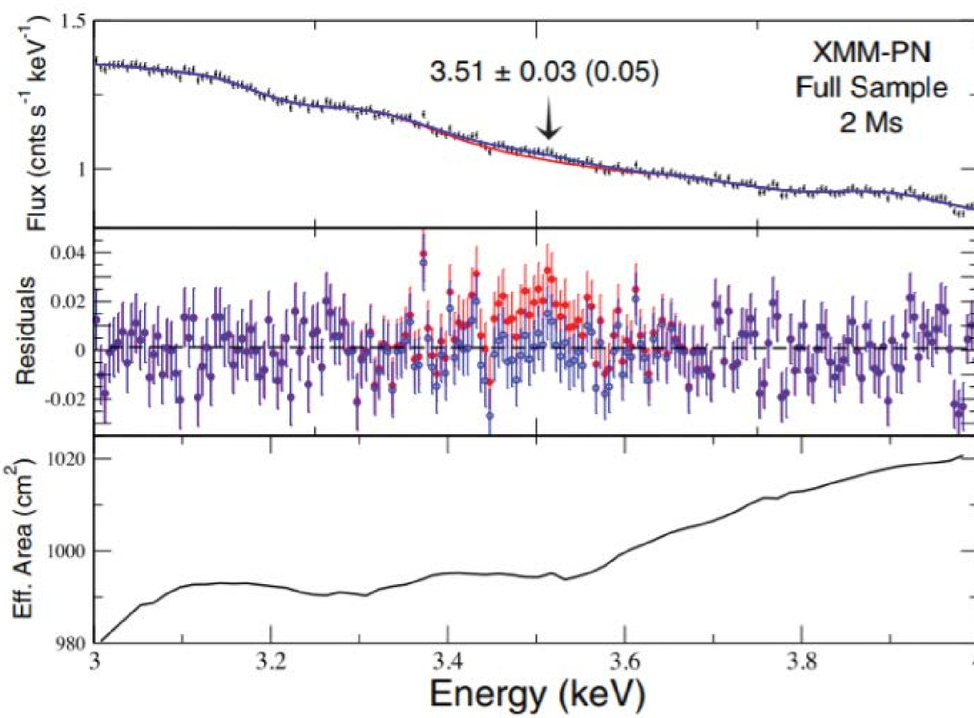

Figure 1: 3-4 keV band of stacked MOS spectra [4]

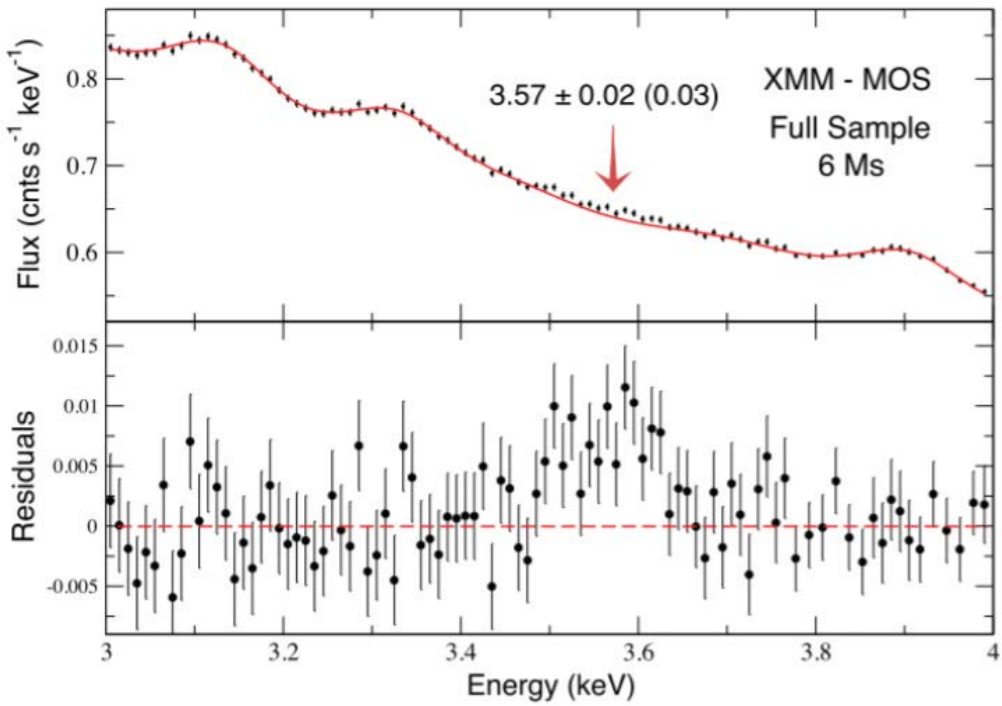

Figure 2: 3-4 keV band of stacked MOS spectrum rebinned to make the 3.57 keV more apparent [4]

Detecting this dark matter candidate by searching for the 3.5 keV X-ray emission line with current observatories has had challenges due to technical limitations. New sensors and equipment must be implemented to reach the sensitivity needed to demonstrate the source of the emission line. Potassium, calcium, or argon, whose radioactive isotopes generate X-ray emission lines that lie within that range, may be mistaken for the 3.5 keV emission line [5]. Current X-ray telescopes also have fairly small fields of view and lack the energy resolution to resolve the weak X-ray lines. Other physicists have performed observations using wide field of view X-ray microcalorimeters as payloads on sounding rockets [6]. Soundings rockets are small research rockets that allow measurement devices and sensors to take data in sub-orbital flight, far above the normal altitude of a weather balloon. Though sounding rockets' sensitivity can compete with the data seen in the large effective area telescopes, they have a short exposure time. Without longer exposure times, it remains challenging to differentiate between the X-ray lines. In order to meet these requirements, small satellites called CubeSats can be used. These satellites allow wide field of view devices to observe X-ray emissions lines for much longer exposure times ranging from several days to several years.

CubeSat specification and design

CubeSat is a specification of picosatellites developed at California Polytechnic State University in order to make experimentation in space more easily accessible to scientists and students. These small satellites are made up of either one, two, three, six, or sixteen units (U) and function completely autonomously **(Figure 3)**. Each unit

is a 10 cm cube that must weigh no more than 1.33 kg. The CubeSat standardization allows for transport as secondary payloads on launch vehicles. They have very strict regulations laid out in their specifications to protect the launch vehicles, payloads, and the CubeSats themselves [7]. Launchers are able to invest in a standard launching system called a P-POD (Poly Pico-satellite Orbital Deployer). This gives all launch companies the ability to launch CubeSats from any of their rockets, which leads to more affordable launches. Other regulations, such as restrictions on pressurization and materials, exist to protect the primary payload and the launch vehicle.

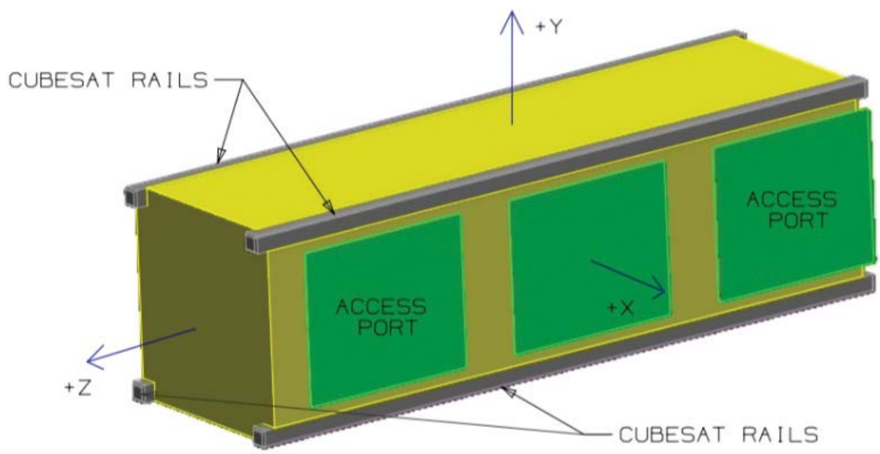

Figure 3: CubeSat drawing that lays out the general specifications for a 3U CubeSat to be launched in a P-Pod including CubeSat rails and general size.

Each CubeSat has its own power supplies, computing systems, attitude determination, attitude control, sensors, thermal management and communication antennas. The standardization allows the use of commercial products and keeps building costs fairly low. Most CubeSats today use PCI/104 standard electronic boards that have stackthrough connectors, allowing for quick easy assembly and electrical interfacing.

A CubeSat that has the capability of detecting the 3.5 keV emission line is being launched by Fermi National Accelerator Laboratory in the next few years. Dark matter as sterile neutrino search satellite (DarkNESS) will continue the search for dark matter as sterile neutrinos using wide field of view optics for long exposure times. The CubeSat's optics will consist of a charge-coupled device (CCD) detector with no optical lenses, allowing it to observe a large portion of the sky. The CCDs that will be used have been implemented in a previous experiment known as Dark Matter in CCDs (DAMIC), which is currently looking for Weakly Interacting Massive Particles (WIMPs) in underground mines. These WIMPs are another candidate for Dark Matter being searched for in the keV energy range. The detector is made of up eight 15 μm × 15 μm megapixels etched onto a 6 cm x 6 cm silicon wafer [8]. When a photon in the 3-4 keV range strikes a pixel on the CCD, it collects charges in potential wells **(Figure 4)**. Eventually these wells roll over and a sequence of voltages are sent back to the controller. There, the voltages are converted to an electrical signal to be read out digitally [9].

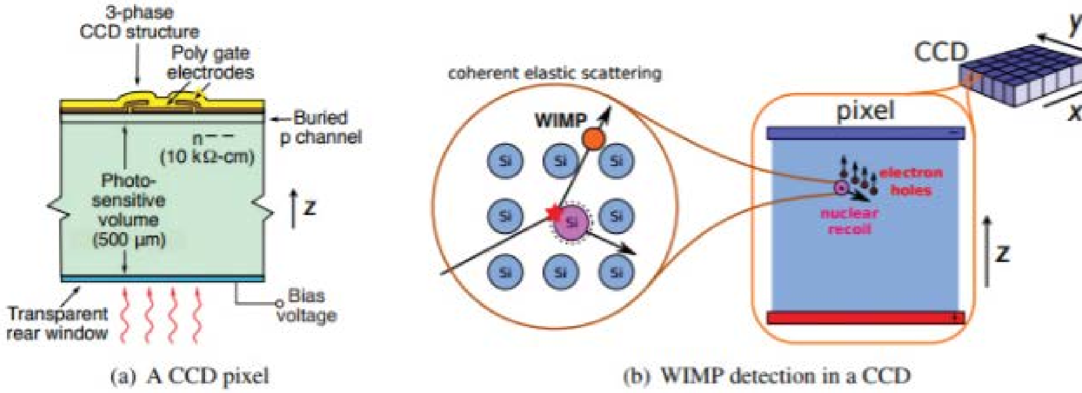

Figure 4: CCD configuration. Detailed explanation of how the pixels in a CCD take an image and how data from that image is transported [8].

In order to minimize thermal noise readout, improve optical resolution, and increase bandwidth, the CCDs must be kept below 170 K while taking data. Due to the close proximity to the Sun in addition to the Earth's albedo radiation, a floating body in the Earth's orbit can obtain high temperatures, making 170 K difficult to achieve. Considerable thermal analysis must take place to ensure the success of the DarkNESS CubeSat.

Orbital candidates

One contributing factor to the thermal analysis is the selection of the orbit. Due to their status of a secondary payload, CubeSat developers are not often able to decide when and where their orbits will take place and must instead plan for a range of possible orbits. The orbit that would allow for the longest experiment time is geostationary orbit. At an altitude of 35,786 km, this orbit allows satellites to remain constantly stationed over a single area of Earth [10]. It is the farthest orbit from the Earth's surface being considered, which allows for less debris and fewer unwanted particle interactions. This orbit is used primarily by weather satellites and global positioning satellites and has limited spaces. It would also be extremely expensive to obtain a spot, and the wait time for a launch would be far too long. In addition to this, CubeSats often cannot obtain the requirements needed for a larger satellite in this orbit. Propulsion, which CubeSats typically lack, is necessary to "knock" the satellite out of orbit when it has completed its mission in order to maintain a low level of debris in this orbit.

The range of orbits from the Earth's surface to 2,000 km is known as Low Earth Orbit (LEO). LEO includes orbits such as polar orbits and the orbit of the International Space Station. A polar orbit is any orbit that passes within 20 degrees of the poles. These orbits have a fairly consistent temperature, as the majority of their orbital time is in solar contact. The upside to this is that the solar panels will work to their maximum capacity. There are two large negatives to this orbit, however. The first is that the temperature will be much higher than desired. Additionally, the CCDs cannot take data directly into the Sun or the Earth. This orbit would drastically decrease the amount of data obtained, as the Sun or Earth would block data collection throughout the majority of the orbit.

The third choice for the DarkNESS CubeSat is the orbit of the International Space Station. The ISS orbit has an inclination of approximately 52 degrees with a perigee height of approximately 403 km and an apogee height of around 408 km. This orbit is approximately ninety minutes and allows for relatively consistent temperature and also a large amount of data collection. In addition to this, it is very easy and inexpensive for DarkNESS to be released from the ISS, as CubeSats can be transported easily with supplies and released from a hatch in the ISS. Due to the benefits of this orbit, it is the chosen orbit for the DarkNESS mission.

Thermal analysis

With the selection of the orbit, thermal analysis can be initiated. Thermal balance of a satellite can be computed using general heat transfer equations. One important characteristic to consider is that the CubeSat will be launched into an orbit that is at high vacuum with very little drag. A high vacuum means that convective interaction can be ignored, while no drag implies that there will be no significant aerodynamic heating. This significantly simplifies the equations used. These equations have been used to calculate the critical hot and cold extremes for the DarkNESS CubeSat. For the hot case, it is assumed that the CubeSat is in direct sunlight with a solar heat flux of 1414 W/m2, an Earth Albedo coefficient of .35, and an Earth heat flux of 260 W/m2 [10]. Using the simplified heat transfer equations for a black-body (emissivity and absorptivity equal to one) the hot case temperature would equate to:

$$T^4 = \frac{J_s + J_a + J_p}{4\sigma} = \frac{1414 + (0.35 \cdot 0.15 \cdot 1414) + 260}{4 \cdot 5.67x10^{-8}} = 23.16°\text{C}$$

The cold extreme temperature assumes the CubeSat is in the Earth's shadow and will receive no direct solar contact or heat flux. The Earth's albedo coefficient would be .25, and the Earth's heat flux would be 220 W/m2 [10]. Using the same equations, the cold case temperature would equate to:

$$T^4 = \frac{J_s + J_a + J_p}{4\sigma} = \frac{0 + (0.25 \cdot 0.15 \cdot 0) + 220}{4 \cdot 5.67x10^{-8}} = -90.94°\text{C}$$

These results show an expected range of approximately -91˚C to 24˚C. This result will not be entirely accurate, as the CubeSat does not behave as a blackbody. The selection of materials will change both the emissivity and absorptivity constants. Emissivity is the measure of how closely a surface approximates a blackbody; for the prior calculations this number is set to 1. A higher emissivity means a higher absorptivity due to Kirchhoff's law [11]. When the absorptivity of an object is higher, the rate at which it absorbs radiation is increased. This would cause higher temperatures overall.

METHODS

Software

Orbital analysis was assessed with the commercially available System's Tool Kit (STK) software (Analytical Graphics, Inc.), which allows engineers to design and analyze dynamic simulations on land, on sea, in air, and, for this project's purposes, in space. A free educational license of STK 11 with Space Environment and Effects Tool (SEET) was used to complete the orbital analysis. SEET evaluates the effects of the near-Earth space environment on the satellite including radiation, the geomagnetic field, particle impacts, and temperature. STK was selected because it is among the top software packages for orbital analysis at a very low cost. For the purposes of our analysis, the ISS orbit was simulated using STK for one year from July 1, 2018 to July 1, 2019.

Computing access

A full year's worth of data was taken and analyzed in STK to determine the most effective dates for the CubeSat's launch and operations. A 3U CubeSat model was created in NX, a CAD modeling software, and imported into STK. After assigning parameters for the orbit, sensors were also modeled. The sensors modeled had a conservative view of 20 degrees in the sky. The orbital constraints were assigned to the sensor to ensure the sensor was always facing the galactic center, specifically Sagittarius A*.

In order to take accurate data, excessive noise must be eliminated. The flux from the Sun and Earth can significantly lower the signal to noise ratio. To eliminate this flux, the CCDs must only take data while the sensors are out of view of both the Sun and the Earth. This constraint was assigned to the sensors. The access between the sensor and the galactic center was then computed from July 1, 2018 to July 1, 2019.

In order to determine the reliability of the data, the sensors must also take data looking out of the galactic plane. This process was then repeated with the CCD sensor pointing out of the galactic plane. This ensures that the signal shows correlation with the Milky Way, as expected from sterile neutrino emissions, which would not expect to be seen in the same quantity outside the galactic plane.

Solar panel simulations

In order to accomplish solar panel analysis, several CubeSat models were created in NX. These part files were converted to blender CAD files, and the materials were delegated to their locations on the satellite. This allowed STK to distinguish between the solar panels and the remainder of the satellite. After this was complete, the model was inserted into STK and an analysis of solar panel performance was completed to determine the amount of energy generated each orbit.

Three solar panel simulations were run with SEET using two different CubeSat models. The trials were run with the same orbital inputs for two orbits. The attitude constraints given to all three of the trials consisted of the CCDs pointing in the direction of the

galactic center with their field of view unobstructed by the Sun or Earth's surface. When the CCDs were not able to take data, the simulations varied in their constraints in order to focus on power generation by optimizing the contact area between the Sun and the solar panels. The first trial consisted of three sets of solar panels along the sides of the CubeSat nearest to the Sun, as pictured in **Figure 5**. When the CCDs are not able to take data, the CubeSat's side aligns with the Sun.

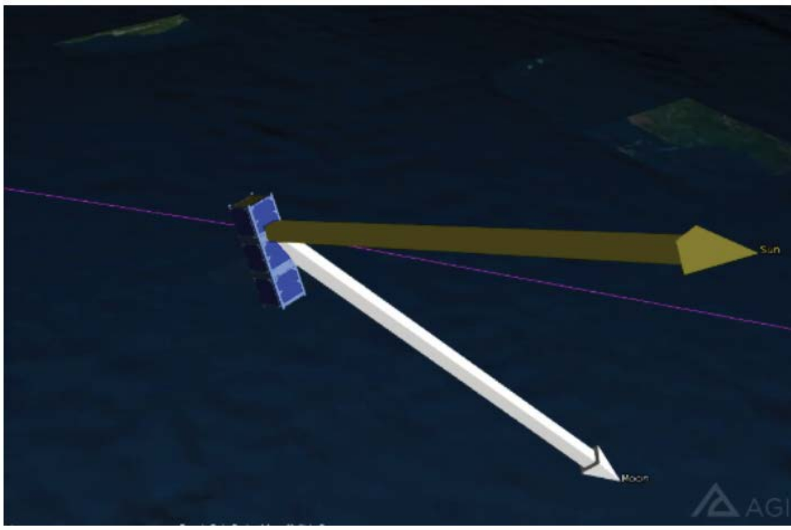

Figure 5: DarkNESS original three-panel approach in STK with one side of the CubeSat constrained with the Sun. The grey arrow shows the Sun constraint, while the white arrow shows the direction of the Moon relative to the satellite.

The second approach consists of the same CubeSat model with one side of the CubeSat at a 45 degree angle to the Sun when the CCDs are not able to take data, as seen in **Figure 6**. In other words, in this alignment the corner of the CubeSat was constrained toward the Sun, allowing two sides of panels to gather light.

Figure 6: DarkNESS three panel approach in STK with the corner of the CubeSat constrained with the Sun. The grey arrow shows the Sun constraint, while the white arrow shows the direction of the Moon relative to the satellite.

Lastly, a new CubeSat model that implemented deployable solar panels was used. As shown in **Figure 7**, these three solar panels are constrained with the Sun at a 90 degree angle when the CCDs are not taking data.

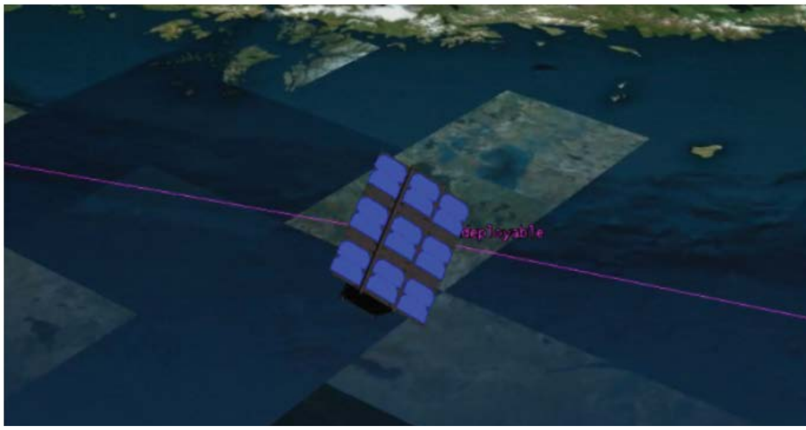

Figure 7: DarkNESS nine panel approach in STK with deployable solar panels with Sun constraint.

RESULTS

Thermal simulations

The range of temperatures the CubeSat will be subjected to was found using STK's SEET package. These results were then compared to the extreme heat transfer results to determine accuracy. Using SEET, STK can simulate the general temperature of the CubeSat as though it is a sphere with a cross sectional area of 0.01m2. The Earth's albedo, which can be thought of as the planet's reflectivity, is selected as 0.35 as a conservatively high estimate. The material selected has an emissivity of 0.81, whereas the absorptivity is 0.87. This is based on the most conservative numbers for aluminum 7075, 6061, 5005, or 5052, which are the only possibilities using the CubeSat standardization. Using these values, the simulation was run for the full year and demonstrated that temperatures oscillated from extremes of -90°C to 50°C, as shown in **Figure 8**.

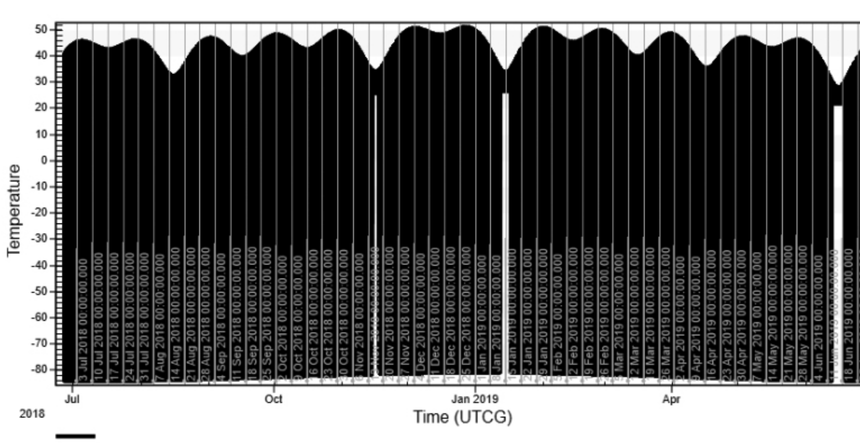

Figure 8: Temperature ranges in degrees C for the DarkNESS simulation throughout the course of one year using α = .87, ε = .81 and Earth Albedo = .35. The CubeSat is modeled as a sphere with a cross sectional area of .01 m^2.

Computing access

Times throughout the orbit when the sensors can be taking data were found using STK. For the first phase, access times occurred when CCDs were able to access the center of the galaxy without interference from the Earth and the Sun. A gap in data collection occurs from November 12th to January 14th, as seen in Figure 7. An additional gap exists between January 18th and January 30th.

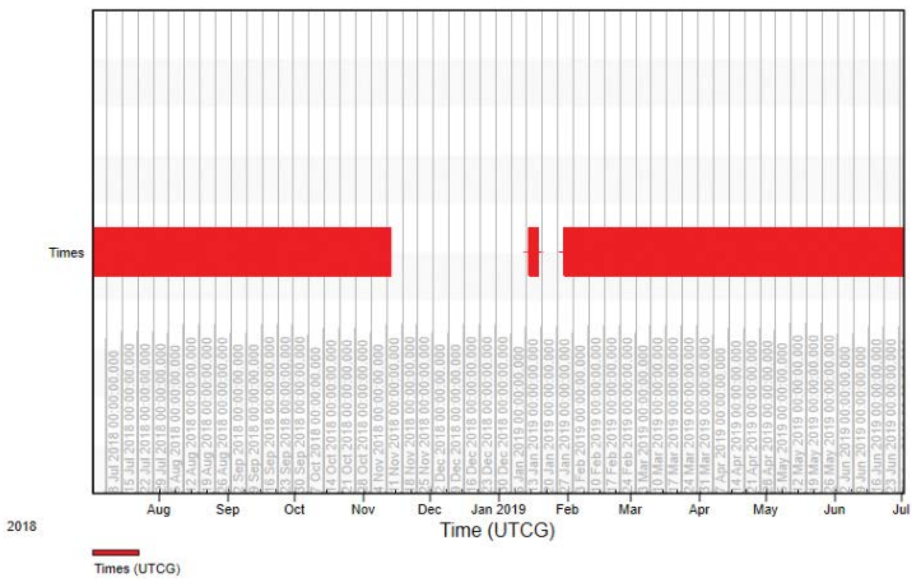

Figure 9: Access computed for CubeSat sensors pointing into the galactic center from July 1, 2018 to July 1, 2019. Grey represents time when access is maintained.

TABLE 1. ACCESS TIMES

Access times computed for CubeSat sensors pointing to the galactic center from July, 2018 to June, 2019.

Year	Month	Total Time (Seconds)	Total Time (Hours)	Rank
2018	July	1306758	362.9883	5
2018	August	1339861	372.1837	2
2018	September	1290931	358.5919	8
2018	October	1332531	370.1476	4
2018	November	506299.8	140.6388	10
2018	December	0	0	12
2019	January	109689.5	30.46929	11
2019	February	1213872	337.1867	9
2019	March	1342346	372.874	1
2019	April	1293115	359.1986	7
2019	May	1337226	371.4515	3
2019	June	1293412	359.2811	6

The tabulated data shows the total amount of time the satellite will be able to take data throughout the month. The longest amount of data collection occurs in March with 1,342,346 seconds, or approximately 373 hours, of data taking.

For phase two, data is collected pointing out of the galactic plane. Again, data collection is restricted to when there is no interference caused by the Sun and the Earth. These simulations show there are no gaps between times of data collection, as can be seen in **Figure 10.**

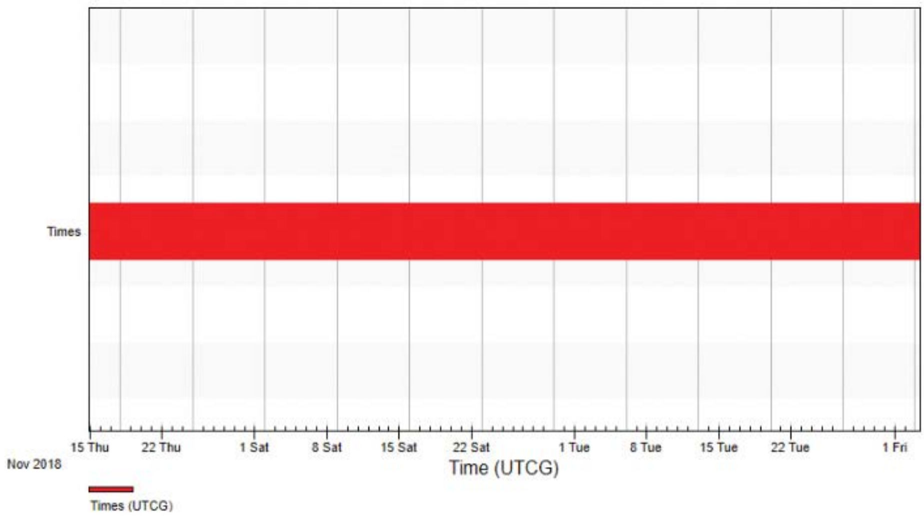

Figure 10: Access computed for CubeSat Sensors Pointing out of the galactic plane from July 1st, 2018 to July 1st, 2019. Grey represents time access is maintained.

Solar panel simulations

The solar panel configurations were then assessed. The first solar panel trial has three sets of solar panels along the sides of the CubeSat align with the Sun when the sensors cannot take data. The results of this approach are shown to have an average of 7.5 Watts when the solar panels are aligned to be taking power, as can be seen in **Figure 11.**

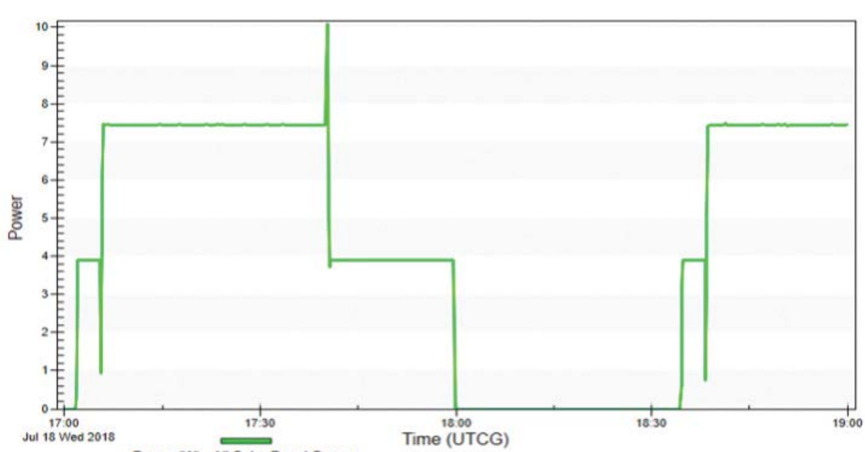

Figure 11: SEET results for three-panel approach in STK. DarkNESS original three panel approach in STK with one side of the CubeSat constrained with the Sun.

The results of the second three-panel approach show a maximum and average of 11 Watts of power when the solar panels are constrained with the Sun at a 45 degree angle, as can be seen in **Figure 12**. The results of third approach with deployable solar panels can be seen in **Figure 13** to have a maximum and average power collection rate of 22.2 Watts during power collection phase.

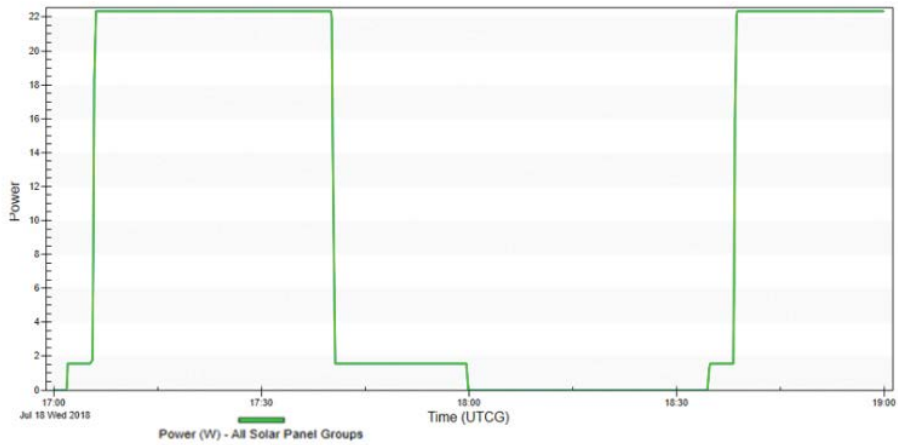

Figure 12: SEET results for second three-panel approach STK. DarkNESS original three panel approach in STK with corner of the CubeSat constrained with the Sun during power collection phase.

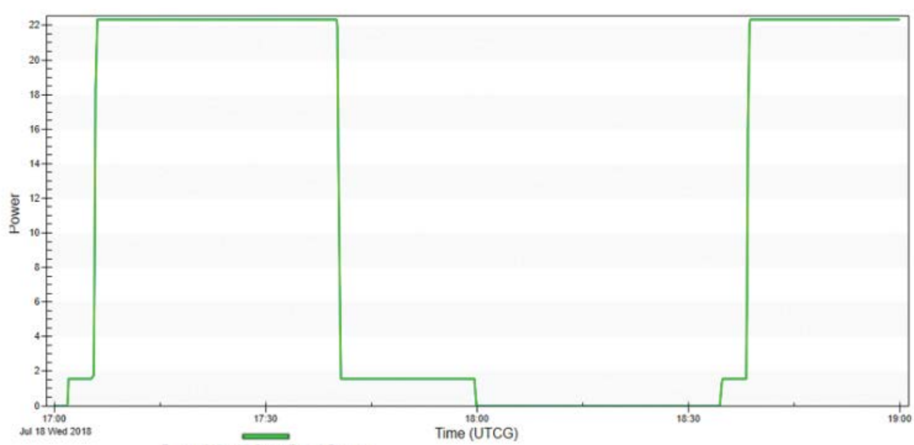

Figure 13: SEET results for deployable solar approach STK. DarkNESS deployable model in STK with solar panels constrained with the Sun during power collection phase.

DISCUSSION

Thermal analysis

Through the thermal analysis, we can see that the lowest temperature achieved by the CubeSat throughout its orbit is still 190 K. It becomes clear that the thermal requirements of remaining below 170 K will be unattainable without major changes to the CubeSat's cooling methods. Even with adjusting the orbit to avoid excessive solar

radiation, the CubeSat will remain above the acceptable temperature range. If data is taken above this temperature, the signal to noise ratio will be too small. Any data taken will be insignificant, as the data cannot be distinguished from noise. In order to reduce the temperature of the CCD sensors, various means of cooling must be taken into consideration.

Passive cooling

One cooling method to consider is passive thermal control, as it requires no input power, is low cost, low volume, low weight, and low risk. Thermal insulation such as Multi-Layer Insulation (MLI) acts as a thermal radiation barrier, lowering the amount of incoming solar flux in order to reduce excessive heat absorption. Unfortunately, the use of MLI will only function properly if extremely accurate attitude control is achieved. Without proper pointing, the MLI could be located on the incorrect side of the CubeSat, causing it to prevent heat dissipation. This would cause the CubeSat to heat rather than cool. Dunmore Aerospace Corporation is the first company to produce MLI for small spacecraft. However, their ranges for cooling are between -23°C to 40°C, well above the required temperatures for DarkNESS [12].

In order to dissipate more heat, thermal louvers may be implemented. These have a larger mass than most other passive cooling options; however, they are also more effective. They work by using bimetallic springs that expand when there is an increase in temperature, causing flaps to open to increase dissipation of radiative heat [13]. This technology, however, is very new and has not been used on a satellite as small as DarkNESS. A drastic decrease in active area may cause a decrease in efficiency.

Figure 14: Passive thermal louver on NASA 6U CubeSat [13].

Active cooling

Without major breakthroughs in passive cooling for nanosatellites, an active cooling element will be necessary. Active thermal methods rely on input power to operate but are much more effective [14]. Unfortunately, the number of active cooling elements that can be implemented in CubeSats are extremely limited. This is due to the satellite's small size, which requires miniaturization of current technologies before implementation.

The most efficient option for an active cooling element is a microcryocooler. These devices are extremely miniaturized coolers that can cool sensors to cryogenic temperatures. Many have been implemented in infrared sensors for military use. Due to their low size and weight, they are optimal for CubeSat missions with cryogenic requirements. Unfortunately, they typically have an extremely high power requirement and cost. The options for microcryocoolers are Stirling cycle, pulse tube, radiator, Peltier, Joule Thompson, cryogens and reverse Brayton coolers [15]. Stirling cycle and reverse Brayton coolers have not yet been miniaturized to the extent that they can be implemented in CubeSats. Radiator and Peltier coolers do not reach cold enough temperatures for the DarkNESS mission and also call for specific orbits that may not be guaranteed [12]. Joule Thompson coolers require an extremely complex design, and the Cryogen coolers have a short lifetime and low reliability. After eliminating unusable designs, only the pulse tube coolers remain as a viable option [15].

Pulse Tube coolers consist of a compressor and a fixed regenerator. Reliability is fairly high, as there are no moving parts at the cold end. They have also already been implemented in CubeSats. After comparing various companies' options for pulse tube microcrycoolers, a conservative estimate for power consumption at the required temperature would be approximately 10 Watts [13]. This would cause the required power input to rise to 20 Watts in order to run the CubeSat.

Access analysis

The time of year that the satellite should be launched is heavily dependent on the amount of time that the CCDs are able to collect data. In order to obtain sufficient data, there should be several months of data collection from the galactic center; Phase 1. This will be followed by Phase 2 with several months of data collection from outside of the galactic plane. Based on the collected data, launching in late summer would be ideal. August has the second longest data collection period at just over 372 hours. If the data collection begins on August 1st, the CubeSat would have approximately 1,242 hours of access time before November 12th. At this time, the satellite's attitude should shift to point outside of the galactic plane, beginning Phase 2 of its observations.

Assuming the access periods maintain consistent every year, late July or early August would be the ideal launch time. Before declaring a launch date, this process of analysis should be repeated for the prospective year in order to verify these results for the selected dates.

Solar panel analysis

Different solar panel configurations were tested in order to determine the optimal set up. Assuming an active cooling element is required, the microcryocooler would have a 10 Watt requirement for power. The CCD controller is estimated to have at most a 5 Watt requirement, whereas the remainder of the satellite should require approximately 5 Watts to run. The overall power budget the solar panels have to obtain in this case is 20 Watts in order to achieve our goal of data collection every orbit. This is very high compared to prior CubeSats, so the solar panels will need to have maximum performance.

The six-panel approach with the 95 degree constraint resulted in maximum power of 11 Watts. For a full ISS orbit, 11 Watts of energy would be collected for around 30 minutes. This would result in 19.8 kJ of energy. This energy could run the CubeSat for approximately 16.5 minutes per orbit if the microcryocooler is required. These minutes would need to be split up between collecting, computing, and transmitting the data. The nine-panel approach generated 20 watts at a sustained level, such that each orbit would yield a total of 39.6 kJ. This wattage would be able to power the CubeSat and microcryocooler for 33 minutes.

Based on the access computed, each orbit has on average 46 minutes of possible access periods. In order to maximize data collection, as much of those minutes should be accessed as possible. The nine-panel, deployable solar panel approach more closely meets the requirements for the success of the mission.

Deployable solar panels also have drawbacks. There is a high chance of failure when deployables are introduced to the design of a CubeSat. Due to the nature of these devices, there is very little that can be done to ensure the success of a deployable part. The advantage to this layout of solar panels is that if the panels fail to deploy, the satellite will be able to function as though the six-panel approach was selected.

CONCLUSION

This analysis has shown that the 170 K or lower temperature requirement to take data can be met using a microcryocooler. The additional power requirements created by the active cooling system are solved via the deployable solar panel approach. An August 1st launch date will allow for the maximum viable time to take data. A CubeSat with these elements is a possible option for identifying a prime candidate for dark matter and answering one of today's prime mysteries in astrophysics.

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