# SPINR Capstone Report

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## Abstract

In 1999 a sounding rocket mission called SPINR was launched from White Sands Missile Range in New Mexico, aimed at the constellation Orion for the purpose of collecting data of the emission spectrum in the UV range using spectrographs that were developed for Boston University's TERRIERS satellite program. Upon analysis of the data, a large amount of 834 Å photons were found without explanation. There are various explanations for this phenomenon, some plausible and others less so. The purpose of this paper is too explore the feasibility of these possibilities, present a detailed analysis of the geometry of the experiment, analyze the data collected, and compare and contrast this to other papers on this issue.


# 1 Introduction

## 1.1 Overview

The Spectrograph for Photometric Imaging with Numeric Reconstruction (SPINR) mission looked at both Orion and Scorpius in the late 1990's and early 2000's. Scorpius contains a nebula with young stars in it that produce ultraviolet emissions, and Orion contains a plethora of dust that could be used for spectroscopic measurements. The light that this paper is concerned with is centered around 834 $\AA$, which means that it is almost impossible for these photons to come from these sources. This is because hydrogen, which is the most abundant element in the universe, has an ionization energy of 13.6 eV, and thus any photon with a wavelength of less than 911 $\AA$ will be able cause ionization and therefore be lost to either absorption or shifted to a lower energy via scattering. The mean free path of a photon in a vacuum environment such as outer space is roughyl $10^5$ kilometers, making it almost certain that no photons of 834 $\AA$ would be able to traverse the 20 light year distance between the Earth and Orion. A local explanation must be sought as to why this phenomenon was observed. The atmosphere of the Earth can be broken into various layers, each containing a different mixture of elements and gasses. At the surface level there is a plethora of molecular nitrogen $N_2$ and oxygen $O_2$ representing roughly 80% and 20% of the atmosphere, respectively. As one moves upwards, this is replaced with hydrogen and eventually $O^+$ in the upper atmosphere. $O^+$ is a perfect candidate for the source of the 834 $\AA$ photons, as there is an emission line in the $O^+$ spectrum centered at that wavelength. The problem is that the experiment was conducted at night, beginning at $4:45 A.M.$ in local time (CMT), and thus no energetic photons should have been available to ionize the $O^+$. The line of sight does eventually meet the umbra and the penumbra of the Earth's shadow, meaning that eventually there is plenty of sunlight available if on goes high enough. The problem with this hypothesis is that $O^+$ does not exist excessively high up in this region known as the exosphere. While there is plenty of fuel for ionization, there is no source. The Goldilocks scenario is that the line of sight meets the umbra in a region sufficiently low in the atmosphere so that there is both an $O^+$ source and sunlight to cause ionization, and subsequent emission of 834 $\mathring{A}$ photons. Another possibility which seems promising is the introduction of conjugate electrons into the picture which would be able to interact with $O^+$ and cause this emission. A final possibility is that ultraviolet light from the sun is reflected off of the moon at some percentage.

## 1.2 Relevant Physics

The first explanation one might wish to consider is the ultraviolet light from Orion is hitting the spectrograph and producing a detection. While this is certainly possible, it is beyond unfeasible as photons of such a high energy are incapable of traversing such vast distances without ionizing hydrogen. A quick mathematical derivation is given to show why this possibility is ludicrous. Consider a beam of light traversing through a medium with n particles per unit volume and a scattering cross-section of $\sigma$. A good assumption is that the drop in beam intensity equals the incoming beam intensity multiplied by the probability of the particle being stopped within the slab. Mathematically, this is equivalent to saying:

$$dI = In\sigma dx \tag{1}$$

This produces the differential equation known as the Beer-Lambert law:

$$\frac{dI}{dx} = In\sigma \tag{2}$$

This has solution $I = I_0 e^{-xn\sigma}$. The probability that an absorption happens between $x$ and $x + dx$ is

$$dP(x) = \frac{I(x) - I(x+dx)}{I(x)} = n\sigma e^{-xn\sigma} dx \tag{3}$$

Finally, the mean free path of a particle is:

$$\langle x \rangle \equiv \int_0^\infty x dP(x) = \int_0^\infty n\sigma x e^{-xn\sigma} dx = \frac{1}{n\sigma} \tag{4}$$

We thus arrive at the conclusion that the probability of a particle going a distance $x$ without an interaction is an exponential decay, and that the mean free path $\frac{1}{n\sigma}$. The density of space being 1 atom per cc (Or $10^6$ particles per cubic meters), and the scattering cross section being roughly $7 \times 10^{-19}\text{m}^2$, which yields a mean free path of $l = 2 \times 10^{12}$ meters, or roughly the distance from the Earth to the sun. The distance from the Earth to Orion being several millions of AU away, the probability that a photon reaches the Earth is 0 to several hundred decimal places. Thus, we must absolutely reject the notion that these photons are from outside of the solar system.

The next possibility that was posited forward was the interaction of sunlight with ionized oxygen in the Earth's atmosphere. While this is a viable solution to the problem, there are some difficulties that arise when one considers the distribution of gasses in the upper atmosphere. Roughly 80% of the atmosphere's mass lies below the stratosphere, and on top of this is where sparse traces $O_2$, $N_2$, $O^+$, and $O^{++}$ exist. This is useful as now there is a source to produce these $834\mathring{A}$ emission lines, but the problem is that the experiment was conducted at night. A very detailed analysis of the geometry of the situation is therefore needed as one needs to know if the $O^+$ gas was in the umbra, penumbra, or completely exposed to the sun during observation. This analysis is conducted in section 3 of this paper.

The final possibility considered in detail is the interaction with conjugate electrons and $O^+$ in the upper atmosphere producing these observations. Conjugate electrons are electrons that are excited at the conjugate point in the Earth's magnetic field and sent along the field lines and eventually crash down into the atmosphere. To see if this is feasible, one needs to find the conjugate point of White Sands Missile Range and see if that region was in the sun during the experiment.

# 2 Geometry

## 2.1 Preliminaries

Like other areas of physics, astronomy has very specialized coordinate systems that help convey information and perform detailed analysis of experiments. Two very common systems are the Equatorial Coordinate System (ECS), and the Horizon Coordinate System (HCS). The equatorial system uses the notion of a celestial sphere to create a fixed coordinate system with the Earth's core as the center. If one draws a line from the north pole to the south pole and then allows this to extend indefinitely, one would arrive at the celestial poles. These points are fixed as the Earth moves. If one were to draw a line around the Earth's equator and then inflate this line to larger and larger radii then one would reach the celestial equator. These are two of the defining characteristics of the Celestial Sphere. The Prime Meridian is define as the great circle that is concentric with the Earth's Prime Meridian at noon during the vernal equinox. This construction means the equatorial system is fixed as the Earth rotates and revolves. The two numbers that define a direction against this sphere are the right ascension and the declination. The next system that we will consider is the horizon coordinate system, also known as horizontal coordinates. This system is dynamic, that is it can have arbitrary origin and thus arbitrary orientation. The origin of this system is the point of the observer. The plane perpendicular to the Earth at this point defines the azimuthal angle, which is the angle between the direction the observer is facing and the direction facing north. The altitude is the angle generated from this plane and the point on the celestial sphere on is considering. Figure 1 offers a visual for this coordinate system, and figure 2 depicts the equatorial coordinate system. The position of the constellation Orion is readily available in the equatorial coordinate system, however the geometric analysis of this problem is far easier when one employs the horizontal coordinate system instead. A quick conversion is therefore needed from one system to another.

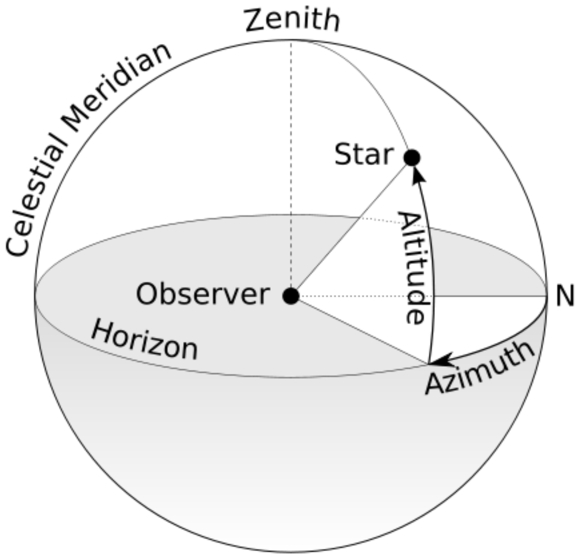


Figure 1: Horizontal Coordinate System, Schombert (2011)

## 2.2 Converting Between Systems

As previously mentioned, the right ascension and declination of the Orion constellation are well known and easily memorizable, they are $ra = 5$, $dec = 5$. To convert back to the horizontal system that will be used for the duration of the analysis, one needs to know what local sidereal time and hour angle are. Normal time is measured by the rotation of the Earth with respect to the sun. Sidereal time is measured as the rotation of the Earth with respect to a fixed star on the celestial sphere. The two systems are different because the Earth also revolves around the sun, causing a discrepancy in the length of day. The hour angle is the angle that the circle formed by the great circle from zenith to pole makes with the great circle formed by the object considered to pole. This angle thus depends on the local time of the observer, hence the name. To get sidereal time one only needs to know the right ascension of the object and the hour angle. This is related by the formula:

$$H + \alpha = LST \tag{5}$$

Where H is the hour angle, $\alpha$ is the right ascension, and LST is the local sidereal time. The derivation of conversions from the equatorial system to the horizontal system is omitted for brevity, but the result obtained after this effort allows one to relate the azimuthal angle and altitude of the object under consideration with respect to an observer to the right ascension and declination of the object. This is formulated as follows: Let $a$ be the altitude, $A$ the azimuthal angle, $\delta$ the declination, $H$ the hour angle, and $\phi$ the observers geographical latitude. Then we have:

$$\sin(a) = \sin(\delta)\sin(\phi) + \cos(\delta)\cos(\phi)\cos(H) \tag{6}$$

$$cos(A) = \frac{\sin(\delta) - \sin(\phi)\sin(a)}{\cos(\phi)\cos(a)} \tag{7}$$

The experiment was done on February 19, 1999 at 4:45 A.M. at White Sands Missile Range, New Mexico which has a geographical longitude of 106°. This translates to a

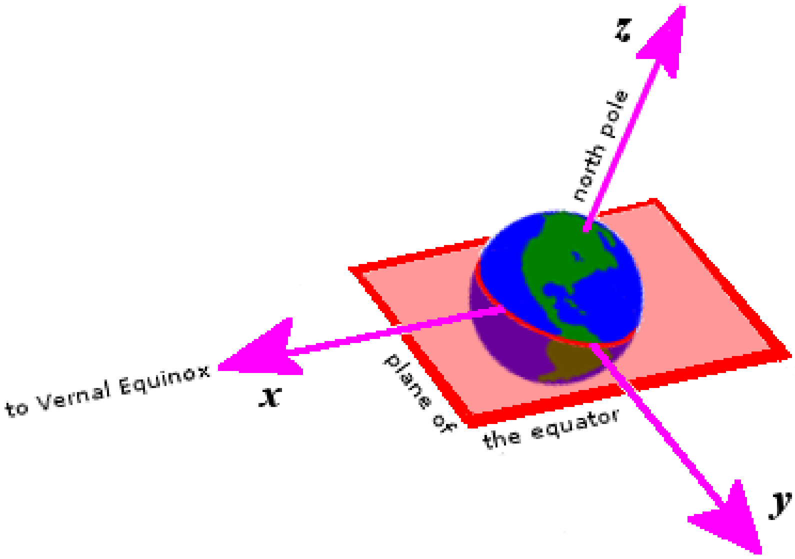


Figure 2: Equatorial Coordinate System, Vollado (2001)

local sidereal time of 15:36, which means the hour angle is $H = LST - \alpha = 10:36$. The latitude of the launch is 32°, and as stated earlier the RA and declination are both 5. Plugging this in gives an altitude of 61.27°. Using this we can now find the azimuthal angle which is 157.8°

### 2.3 Geometric Analysis

The geometric objects that this experiment is concerned with are lines and cones, which are easily described in terms of Cartesian geometry. For practical purposes, however, two Cartesian systems are needed. They will be $x, y, z$ and $x', y', z'$. The z axis will be south pole to north pole, the x axis being the line from pole to prime meridian. The y axis is thus the unique right handed vector that is perpendicular to both (0° latitude, 90° longitude east). The z' axis will be taken as the line from the center of the Earth through the center of the sun. At the time of the experiment the sun had a declination of -11.322, and as the local time was 4:45 A.M., the sun was directly above the point 2.14° east, 11.32° south. The x' and y' coordinated do not really matter, and can be chosen based on convenience in the following equation. The set of points that lie on a line in $\mathbb{R}^3$ take the form

$$(a, b, c) = t(p_0, p_1, p_2) + (1 - t)(q_0, q_1, q_2) \tag{8}$$

Where $p_i$ and $q_i$ are the coordinates of two points on the line, and t is the parameter. It would be most convenient if the parameter was the z' axis, allowing us to use the (x,y,z) coordinates to describe it. The first point is rather obvious, the origin $(0, 0, 0)$. The second point is at 2.14° east, 11.32° south. This corresponds to $x = R\cos(2.14)\cos(-11.32)$, $y = R\sin(2.14)\cos(-11.32)$, $z = R\sin(-11.32)$, where R is the radius of the Earth. This point is $x = 0.98R$, $y = 0.36R$, $z = -0.20R$. The parametric equation for the z' axis in the unprimed coordinates is therefore:

$$(x, y, z) = z'(0.98R,\ 0.36R,\ -0.20R) + (1 - z)(0, 0, 0) \tag{9}$$

It is very important to note that in this formulation the unprimed coordinates are free to be any unit of length, by the primed are now measured in intervals of Earth radii.

The equation of a cone is central to the rest of the conversation. We need to find the equation of the cone which contains both the Earth's surface as well as the Sun's. The equation of a cone concentric with the z' axis is:

$$(z' - z_0)^2 = \alpha^2 x'^2 + \beta^2 y'^2 \tag{10}$$

The key thing we want to find here is $z_0$, which is the point of the cone. We know the cone lies tangent to the Earth's surface, thus it is a circular cone and $\alpha = \beta$. The sun's ray's strike the edge of the Earth at roughly a great circle. This is when z' = 0. This is the first constraint of the cone.

$$z_0^2 = \alpha^2 (x'^2 + y^2) = \alpha^2 \tag{11}$$

This is because we chose the unit length of the axis to be an Earth radii. The second constraint is that this cone lies on the edge of the sun as well. The sun is 23,250 Earth radii away, our z' value, and has a radius equal to roughly 110 Earth radii. This gives us the following:

$$(23,250 - z_0)^2 = 110^2 z_0^2 \tag{12}$$

This has two solutions, one positive and one negative. The positive solution is a point that lies between the sun and the Earth, which is the center of the penumbral cone. The negative solution lies behind the Earth and corresponds to the umbral cone. These solutions are $z' = -213$ Earth radii and $z' = 210$ Earth radii. This two points have the following geocentric coordinates:

$$x_{umbra} = -209R,\ x_{penumbra} = 206R \tag{13}$$
$$y_{umbra} = -77R,\ y_{penumbra} = 76R \tag{14}$$
$$z_{umbra} = 43R,\ z_{penumbra} = 42R \tag{15}$$

We may now rid ourselves of the unprimed coordinates. The next step is to find the equation of the line pointing from the rocket to the constellation Orion. We first must find where White Sands is in our Cartesian coordinate system. White sands lies at 106° west and 32° north. This corresponds to the following:

$$x_{White\ Sands} = -0.24R \tag{16}$$
$$y_{White\ Sands} = 0.82R \tag{17}$$
$$z_{White\ Sands} = 0.53R \tag{18}$$

A unit vector in this direction is therefore $\mathbf{r} = \langle -0.24, 0.82, 0.53 \rangle$. Since all we know of Orion is it's coordinates in the horizontal coordinate system, we need to find the tangent plane to the Earth at this point to find the parametric equation of this line. The plane tangent to a point $P$ and perpendicular to vector $\mathbf{r}$ can be found in the following manner: As every vector in the plane will be perpendicular to $\mathbf{r}$, let us construct the following arbitrary vector $\langle x + 0.24R, y - 0.82R, z - 0.53R \rangle$. This is a position vector center on White Sands. We thus have $\mathbf{r} \cdot \langle x + 0.24R, y - 0.82R, z - 0.53R \rangle = 0$, which gives the following equation of a plane:

$$0.24x + 0.82y + 0.53z = 0.9R \tag{19}$$

The horizontal Coordinate system defines north as one of its axis. The vector pointing north contained in this plane will point directly to the z-axis. That is, at the point $x = 0,\ y = 0,\ 0.53z = 0.9R^2$, the plane will intersect the z-axis. This corresponds to $z = 1.7R$. The vector point north is then the vector obtained by traveling inwards towards the Earth's core, and then up $1.7R$ along the z axis. That is, $\mathbf{N} = \langle 0.24R, -0.82R, 1.7R\rangle$. The azimuthal angle of the constellation is 158°. This defines a half-plane perpendicular to the tangent plane. We can find a vector pointing in this direction by solving a system of equations. The first constraint is that the vector is in the plane. The second constrain is that this vector, call it $\mathbf{A}$, satisfies $\mathbf{A} \cdot \mathbf{N} = |A||N|\cos(158)$. The third constraint, which we impose freely, is that $|A| = 1$. This gives the following:

$$\mathbf{A} = \langle x, y, z\rangle \tag{20}$$

$$\mathbf{A} \cdot \mathbf{r} = 0 \tag{21}$$

$$\mathbf{A} \cdot \mathbf{N} = |A||N|\cos(158) = |N|\cos(158) = -1.78R \tag{22}$$

$$x^2 + y^2 + z^2 = 1 \tag{23}$$

Physical consideration about the Orion constellation lead to another constraint, that is that Orion is in the northern hemisphere of the celestial sphere. This gives $z = -0.8,\ y = 0.57,\ x = 0.19$, where we have finally chosen R in units of km. The altitude is 61.3°, which yields the vector $\mathbf{O} = \mathbf{A} + \alpha\mathbf{r}$, where $\alpha$ is chosen such that $\mathbf{O} \cdot \mathbf{r} = |O|R|\cos(61.3)$. This gives an $\alpha$ value of $|A| - \mathbf{A} \cdot \mathbf{r}\cos(61.3) = 0.9$. We finally have our vector which points from the core to Orion.

$$\mathbf{O} = \langle -0.03, 1.31, -0.29\rangle \tag{24}$$

(O for Orion). Now, the rocket was roughly 300 km above ground, so we adjust for this accordingly:

$$x_{Rocket} = -0.26R \tag{25}$$

$$y_{Rocket} = 0.88R \tag{26}$$

$$z_{Rocket} = 0.57R \tag{27}$$

We now have a point an a vector, which is enough to describe a line. The line from the rocket to Orion is

$$\Gamma(t) = t(-0.29R, 1.19R, 0.28R) + (1-t)(-0.26R, 0.88R, 0.57R) \tag{28}$$

We conclude this analysis by find the point where the line $\Gamma$ meets the cone found in the primed coordinates. This is obtained in a rather straight forward manner by finding the unique line within the cone that intersects the line $\Gamma$. In the geographical cartesian coordinates we've been using, the point of the cone is 213 Earth radii away. The Earth being 1 Earth radii means that the distance from the point of the cone to the points where the cone touches the Earth is $d = \sqrt{213^2 + 1^2} \approx 213$ Earth radii. This means, if one recalls equations 13-15, that $\sqrt{(x+209R)^2 + (y+77R) + (z-43R)^2} = 213$ and $x^2 + y^2 + z^2 = 1$. This gives very complicated equations $z = z(x)$ and $y = y(x)$. The are not horrible, as they are merely square roots and quadratics, but the coefficients are a nightmare. Lastly, this line must intersect the line $\Gamma$. This means the vector from the umbra point to the surface of the Earth dotted with the vector from the line $\Gamma$ to the surface of the Earth must be equal to the product of their magnitudes. When all of this is combined together, you get a height of over 1,000 kilometers. That means the point where the line of sight of the rocket meets the umbra cone is way beyond the thermosphere and well into the exosphere. This concludes the geometric analysis of the experiment.

# 3 Summary of the Geometric Analysis

In the long and complicated analysis of the geometry of the experiment it was found that the height of the umbra where the rocket was facing is over 1,000 km. This is indeed a lower bound, as a lot of rounding up took place at the subsequent steps of the analysis to make the numbers much easier to keep track of. A more detailed analysis can easily be made by simply being more exact (This includes using a more exact radius of the earth, a more exact distance from the point of the umbra cone, and so on). However, this is not really necessary as a lower bound of 1,000 km certainly creates problems. The key ingredients needed for the presence of 834 emission lines are $O^+$ or $O^{++}$, and a combination of both would certainly help. This high up in the atmosphere, however, means the density of air is very low. The Gamma Ray Large Area Telescope (GLAST) has a simple yet effective model of the density as a function of height which exponentially decays with height. 80% of the mass of the atmosphere lies within the first 30 km, meaning once one goes beyond the thermosphere there is almost nothing. This is troubling, as in the region where there is enough sunlight to ionize the $O^+$, there simply isn't any $O^+$ available. The gas that is available is mostly hydrogen, anyways. We now have one of two options before us: The 834 is not coming from direct interactions with the suns rays, or there is a lot of $O^+$ high up in the atmosphere. The latter explanation doesn't seem likely, as this experiment has been performed in various ways looking at various parts of the sky, all of which obtained similar results. We must therefore look towards other explanations for the observed phenomenon.

# 4 Conjugate Points

Another possibility is that the 834 lines are the result of collisions between conjugate electrons and $O^+$ in the upper atmosphere. Conjugate electrons are electrons that are excited in the atmosphere, enough so that they are ejected into the upper atmosphere and then follow the Earth's magnetic field to it's conjugate point. From Gauss' Law of Magnetism, $\nabla \cdot \mathbf{B} = 0$, each point on the surface of the Earth has a unique conjugate point. A map of the magnetic latitude lines can be found in figure 3. The longitude lines are formed by taking the gradient of these lines. To find the conjugate point, on simply needs to find the path that minimizes the following functional equation:

$$J[\mathbf{F}] = \oint_c \mathbf{F} \cdot \mathbf{dl} \tag{29}$$

Where F is the magnetic force. As the magnetic force is incapable doing work on an object, the path that does this will make the integral equal zero and follows the magnetic field lines through the earth. The conjugate point is where this path intersects with the Earths surface. Simply by following the gradient of the lines in figure 3 allows one to gain a rough estimate as to where this point will be.

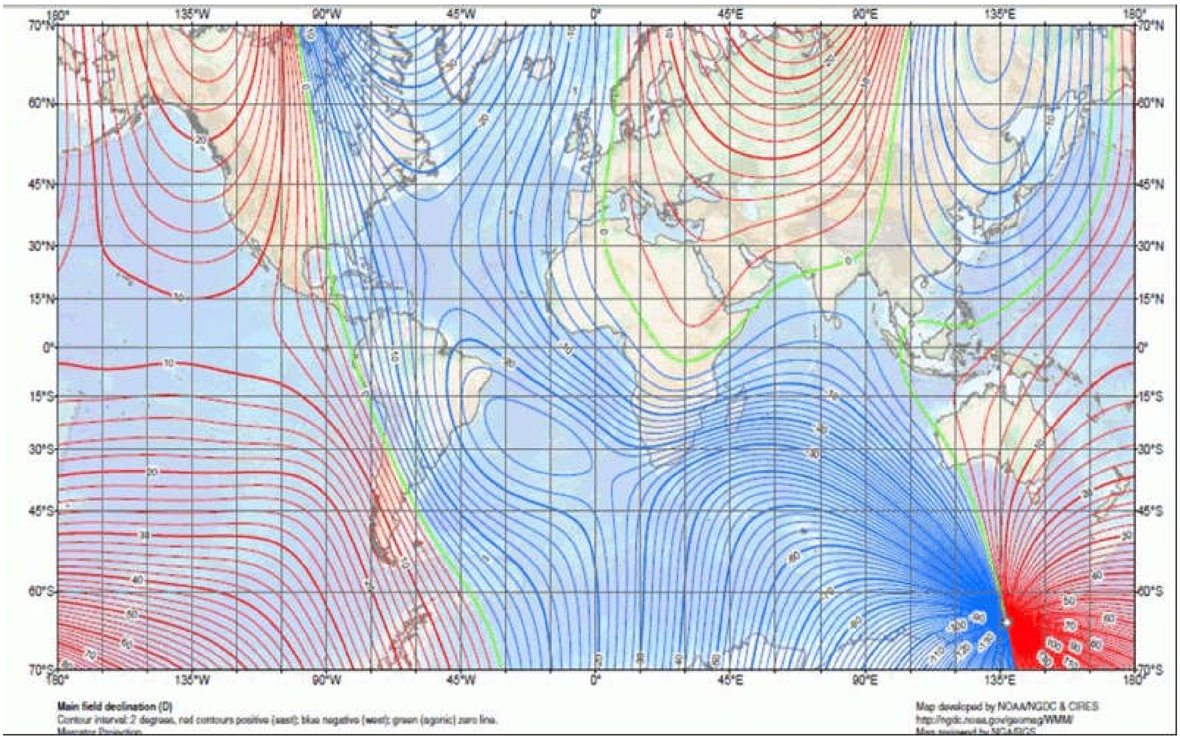


Figure 3: Geomagnetic Latitude Lines

A paper by Kumar, Bowyer, and Paresce was able to explain a similar observation via this technique. When a similar analysis is performed for this experiment, it is found that the conjugate point of White Sands sits slightly north of Antarctica, but on the same face of the globe. It is therefore impossible that conjugate electrons caused this observation, as the conjugate point was also in the dark so no sunlight would be able to excite these electrons. Again, another explanation must be sought.

# 5 Reflections from the Moon

One solution that has been proposed is the reflection of ultra-violet light from the moon. A detailed analysis of this is in the works, and whether or not this is feasible is currently unknown. The moon has an albedo of 0.12 for visible light, which is a lot of reflected light that enters the Earth's atmosphere at night. The problem with this is the albedo for light is not a constant, and it decreases in the ultraviolet range. Another shortcoming is the location of the moon is crucial to the observation, and as the experiment repeatedly makes the observation, one should expect the moon to be similarly positioned for all flights. This will be looked into in more depth in the future.

# 6 Data

We now present the data that was gathered during the second flight of the SPINR rocket. This is the experiment that was aimed at the Orion constellation, for which the geometric analysis was performed. The large spike that is seen in figure 4 is from Lymen-$\alpha$.

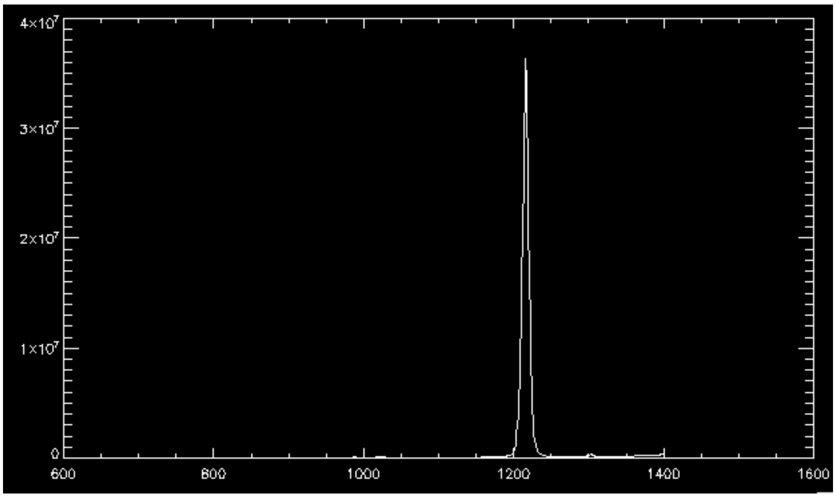


Figure 4: The Entire Spectrum

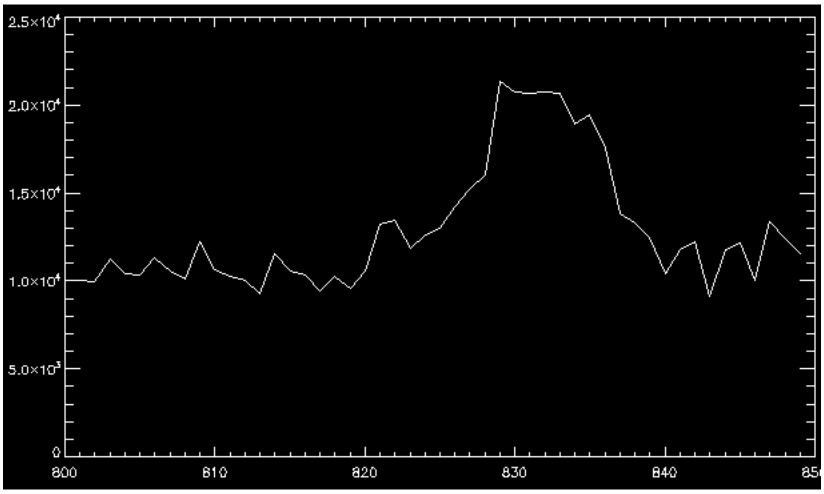


Figure 5: The 834 Spectrum

The data in the region of $834\mathring{A} \pm 15\mathring{A}$ gives a result of 8 Rayleigh's. The Kumar paper mentioned earlier had a result of 15 R with an uncertainty of 5. This paper used the conjugate point hypothesis to explain the observation, but as this paper has demonstrated that is most unlikely for the SPINR experiment. Thus, we are left with the possibility that the $O^+$ can exist high in the atmosphere, or that there is some new mechanism for exciting oxygen in the dark.

# 7 Conclusion

From the analysis of the geometry we have been able to disregard the possibility of oxygen excitations in the lower atmosphere as a result of interactions from the sun. We have also been able to discredit the notion that conjugate electrons are responsible for this phenomenon as well. There are still several possibilities to explain the observation of 834 lines that need a more detailed investigation. These possibilities include oxygen in the upper atmosphere, UV rays from external sources other than the sun, and perhaps some mechanism for creating dark excitations that needs further consideration.

# 8 References

1. Kumar *et al.*, 1977
2. Cook *et al.*, 2002
3. Cook *et al.*, 2009
4. Vollado, 2001
5. Schombert, 2011
6. GLAST at Stanford, 2015