An Analysis of Fireballs from Willamette's D6 AllSky Survey

by

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Presentations and publications

P. Gibson, Analyzing Fireballs from Willamette's D6 AllSky Survey, Oral Presentation at Willamette University, Research Seminar I: Status Report Presentation (December 2018)

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Abstract

Mr. Worldwide to infinity You know the roof on fire We gon' boogie oogie oggi, jiggle, wiggle and dance Like the roof on fire We gon' drink drink and take shots until we fall out Like the roof on fire Now baby give a booty naked, take off all your clothes, and light the roof on fire Tell her baby baby baby baby I'm in fire I tell her baby baby baby I'm a fireball Fireball I saw, I came, I conquered Or should I say, I saw I conquered, I came They say the Chico on fire and he no liar While y'all slippin' he runnin' the game Now big bang boogie Get that kitty little noogie In a nice nice little shade I gave Suzie a little pat up on the booty And she turned around and said Walk this way I was born in a flame Mama said that everyone would know my name I'm the best you've never had If you think I'm burning out, I'm never am I'm on fire I'm on fire I'm on fire I'm on fire Fireball Sticks and stones may break my bones But I don't care what y'all say 'Cause as the world turns, y'all boys gonna learn That Chico right here don't play That boy's from the bottom, bottom of the map M.I.A U.S.A I gave Suzie a little pat up on the booty And she turned around and said Walk this way I was born in a flame Mama said that everyone would know my name I'm the best you've never had If you think I'm burning out, I'm never am I'm on fire I'm on fire I'm on fire I'm on fire Fireball We're taking it, we're taking it We're taking it down We're taking it, we're taking it We're taking it down We're taking it, we're taking it We're taking it down We're taking it, we're taking it We're taking it down We're taking it, we're taking it We're taking it down We're taking it, we're taking it We're taking it down We're taking it, we're taking it We're taking it down We're taking it, we're taking it We're taking it down Now we're bring it, we're bring it We're bring it back We're bring it, we're bring it We're bring it back We're bring it, we're bring it We're bring it back We're bring it, we're bring it We're bring it We're bring it back We're bring it, we're bring it We're bring it back We're bring it, we're bring it We're bring it back We're bring it, we're bring it We're bring it back We're bring it, we're bring it We're bring it back Fireball Fireball Tell her baby baby baby baby I'm in fire I tell her baby baby baby baby I'm a fireball

Table of Contents

List of Figures

1 Introduction

Based on a rough estimate, there are about 10 000 trillion ants, 7.6 billion humans, and a few million elephants in the world. When considering this small[1] data set, one might come to the conclusion that there are more small objects in the world than there are large objects. It so happens that this conclusion not only holds true on Earth, but it also holds true in our universe.[2] In our solar system, there is one star, eight planets, and an almost incomprehensible number of small rocks traveling through space.

Similarly to distances in space, velocities of objects in space are of higher orders of magnitude than those observed on earth.[3] For example, the Earth travels at approximately 30 km/s while small rocks can travel between 11 km/s to 70 km/s. The speeds of these rocks exceed the muzzle velocity of a bullet.[4] When we observe a meteor shower, we are witnessing a barrage of these bullet-like rocks. Fortunately for mankind, Earth's atmosphere provides a protective shield consisting of a condensed array of particles.[5] Condensed is a term being used in relativity to the vacuum of space in which these rocks spend the majority of their lifetime.[6]

As a rocky object travels through Earth's atmosphere, it collides with particles and burns in a phenomena known as ablation. The result is a release of energy in the form of both heat and light. The objects, which ignite in a fiery ball are called fireballs.[7] For large enough fireballs, the light produced in ablation can be seen from the human eye as shooting stars.[8]

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[1]these numbers are small?!

[2]I think you need a sentence to bridge these two.

[3]So I get what you are going for here, but this is a convoluted sentence.

[4]probably want a citation here

[5]The start of this sentence is good but I don't like the end as much

[6]I'd just bake this definition into the previous sentence

[7]Careful here, technically fireballs are only the brightest meteors

[8]I'd remove this sentence and provide more context about the different magnitudes they might be seen at.

By observing the photometric (visual) magnitude, duration, and other properties of individual fireball events, an observer can estimate impact energies and sizes of these near-Earth rocky objects. Given a large enough sample size, observers can also determine the flux, or the number of events within a specific area per time, of fireballs of varying sizes and energies.[9]

While cameras set up by organizations such as NASA and the Spanish Meteor Network (SPMN) provide useful and precise measurements of fireball events, they lack flexibility and affordability. Often rendered immobile due to their connection to powerful computers, these systems provide only a small piece to the puzzle of fireball observation.[10] Any individual camera system can only observe up to around 0.03 percent of earth's total sky.[11]

This project aims to analyze the feasibility of the Willamette D6 AllSky camera, a new alternative camera system for conducting fireball research. Occupying about the same space as a traffic cone, this camera is easily transportable and can be replicated at a fraction of the price of the more expensive professionally used systems.[12] By comparing flux rates measured through the analysis of data taken from Willamette's D6 AllSky camera to more well-recognized systems, we will determine if our setup is a practical option for amateur astronomers interested in contributing to fireball research.[13]

This paper is broken up into several sections for ease of reading. Chapter 2 details useful information surrounding fireballs, their importance, existing research, and the theory necessary to calculate flux rates. [11][14]

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[9]Paragraph only has two sentences.

[10]What do you mean by small piece here?

[11]Oh, is this what you meant? I feel like this paragraph needs something more then.

[12]Should be careful with language here, the camera itself is basically the same as in the other systems. The supporting infrastructure is what differs.

[13]Possibly break this sentence up and clean up the wording. Its possibly the most important sentence in your introduction, so don't skimp on it.

[14]Wait, why is this cited here? It seems super out of place...

2 Background

Thanks to a protective atmosphere, Earth[1] can withstand impacts from dust to boulder-sized objects traveling faster than bullets without so much as a dent on Earth's surface. While most of these near-Earth objects are extremely small and don't leave much of a trace, the larger objects can leave a light trail[2] visible from Earth's surface as they burn up in our atmosphere. In this chapter, we will discuss the classification of near-Earth objects, the camera system and theory behind our analysis, the current photometry tools we have, along with other existing surveys.[3]

2.1 Description of Fireballs

When considering types of near-Earth objects, many names come to mind: asteroids, meteors, meteorites, and fireballs are all often used interchangeably. However, there are several key distinctions between these objects. Asteroids are the largest of this group and are generally over $10\,\mathrm{m}$ in diameter [10]. These large objects are responsible for large craters that are visibly present on the moon.[4] Meteoroids are anywhere between $10\,\mathrm{\mu m}$ and $10\,\mathrm{m}$ and are far more numerious than their asteroid cousins.

Meteoroids that pass through Earth's atmosphere become meteors. As meteors pass through the atmosphere, they begin to ablate, or release light.[5] This phenomena happens because the interactions between meteor molecules and air molecules produce lots of energy, some of which goes into the production of light.[6] The amount of released light that reaches an observer can be measured in terms

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[1]Oh sure, now you start capitalizing it...

[2]I can guess, but what do you mean by "light trail" here?

[3]What exactly about other existing surveys?

[4]Lots of "large" in these past two sentences

[5]Ablating and releasing light are not synonymous

[6]Where is the energy coming from? What exactly are these "interactions"?

of apparent magnitude. Magnitude is represented on a $\log_1 0$ scale where dimmer objects are represented by high numbers and brighter objects are lower.[7] If the meteor releases visible light below an apparent magnitude of -4 qualify as bolides, or fireballs.[8] For reference, Venus is a magnitude -4.4 planet while the dimmer Jupiter has a magnitude of -2.1 [9].[9] If an object is massive enough to withstand the pressures of Earth's atmosphere and make it to the surface of Earth, it is classified as a meteorite. These are extremely[10] uncommon, but can provide valuable information about the rock's origins. Figure 2.1 summarizes the relationship between these 4 terms.
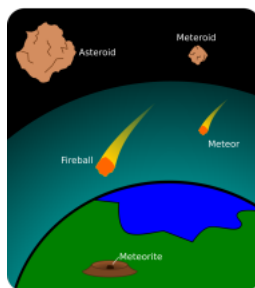

Figure 2.1: A depiction of near-Earth object classification.[**Include a description of each type in the caption itself. Imagine someone not reading the text and just reading the captions. And why is it so tiny?**]

We may further classify near-Earth objects into two categories: sporadic events and meteor shower events.[11] Meteor showers occur when Earth's orbit crosses paths with the orbit of a collection of debris. Such collections often orbit large masses such as Jupiter or the sun [11]. For example, the Perseid meteor shower has a highly elliptical orbit around the sun as seen in Figure 2.2. A majority of the composition of these showers stems from the decomposition of comets throughout space.[12]

In contrast, there is debris in space that is not connected to any meteor shower. These are called sporadic events.[13] Because gravity tends to bring objects together, we see mostly collections of debris.[14] However, when objects escape their

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[7]This seems an obvious place for the actual equation and reference.

[8]Sentence is convoluted.

[9]Venus's magnitude changes as it goes through its phases, so you might want to be specific about which phase you are talking about.

[10]how much so?

[11]We aren't really classifying the objects here, rather the fireball events. And the type of event tells us information about the object.

[12]I get it, but that is a heck of a confusing sentence.

[13]Again, just nomenclature. The event and the object are separate things.

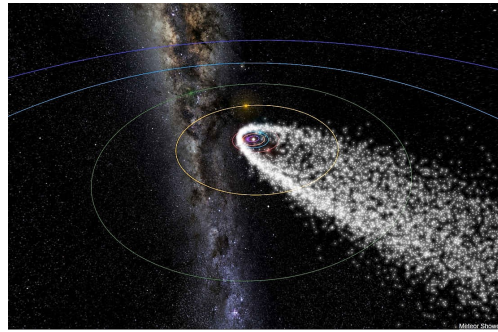[14]What are you trying to say here? This is confusing.

Figure 2.2: The Perseid meteor shower and its relation to our solar system.

collection due to other interactions (gravitational or electromagnetic), they still have a chance of colliding with Earth.[15]

[16]Studying these near-Earth objects can give us good estimates for how many objects you might expect to see pass through a given area of space within a specific amount of time. This measurement is called flux. By determining flux, we can more accurately predict the likelihood of objects in space being hit by near-Earth objects. Although the case may have been an extreme one, the space satellite Olympus was struck and destroyed by a meteoroid during the Perseid meteor shower in 1993 [2]. Additionally, given the relationships between the number of objects hitting earth per time for different objects, we can estimate the probability of extremely large impacts on earth. These estimates, similarly to predictions surrounding volcanic or earthquake activity, give us insight into past events and help us foresee likelihoods of future events.

2.2   The D6 AllSky Camera

The Willamette University D6 Allsky[17] camera was created in 2016 to capture images of fireballs streaking through the night sky. The aim of the project was to create an economically feasible and highly mobile observational system. Enclosing a state-of-the-art camera system in a portable structure along with necessary supporting devices, including a controlling Raspberry Pi, Kyle McSwain alongside Dr. Jed Rembold were able to get a functioning camera system [7].[18] The assembly resembles a Star Wars astromech droid, and acquired its name from this inspiration. The enclosure with visible camera is shown in Fig. 2.3. The

---

[15]This seems an odd end to the paragraph.

[16]I might almost think this whole paragraph could be moved to the Introduction and fit there better.

[17]probably shouldn't be capitalized

[18]This sentence is still really long. I'd break it up more.

D6 allsky camera is currently operational and has been gathering data since the summer of 2018. Below, we will discuss the design of the D6 allSky camera while also highlighting what makes it significant.

Figure 2.3: The Willamette D6 AllSky Camera (2016) Paired with a little imagination it resembles an astromech droid from Star Wars.[We should get a new image of this, as it has the sealing cowl along the top now.]

2.2.1   Composition

The components of the D6 allSky camera are comprised primarily of 5 different pieces: the camera housing, a CCD camera, a thermostat, a digitizer, and the Raspberry Pi to control everything. The acrylic dome and PVC shell form the exterior of our system. The dome itself is a transparent half sphere that sits on top of a PVC cylinder that holds the system together. It[19] acts as a protective layer between the camera and the outside environment. Without this feature, the camera would be subject to rain, snow, dew, bug contamination, and other undesired effects.

The CCD camera is perhaps the most important feature of the camera[20]. The Watec 902H2 CCD camera uses a fish-eye lens to capture incident light from the night's sky.[21] It was chosen due to its extremely high sensitivity and resolution [7].[22] While some fireball camera stations are composed of multiple high resolu-

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[19]the dome or the cylinder?

[20]too many cameras

[21]So the camera is separate from the lens. Probably should talk them separately.

[22]Hmmm, it'd be nicer to source some specs here rather than an old thesis.

tion, more narrow lensed cameras, the D6 AllSky system only contains one camera mostly for economic reasons.[23]

Because of its constant use throughout the night, the system itself can get very warm and therefore needs some thermal regulation. The camera is kept at a relatively constant temperature by a thermostat and a fan system. [24]

The camera outputs an analog signal which requires the use of a digitizer before it can be processed by the Raspberry Pi. The coaxial signal is sent to the digitizer before connecting to the Raspberry Pi via USB.

[25]The Pi then takes the frames from the camera's running video and scans for systematic changes in brightness. These changes then trigger the recording and storage of a new video, which is saved for further photometric analysis. By combining these parts into one system, we are able to capture and catalog fireball events.

2.2.2   Uniqueness

[26]

While there are several similarities in the composition of our allSky camera to existing systems, there are several key differences. The most prominent of these are the size, versatility, and cost of our system. Around the size of a basketball, the D6 allSky camera is extremely compact. Not only is it small, but it only relies on a single power chord for power. Because of this, the camera can be easily picked up and relocated to any setting that has a power source. The system has low power requirements and it should be possible to run from a battery if remote placement is desirable in the future. Most other[27] systems are rooted to extremely powerful computers that have little to no mobility as shown in Fig. 2.4.

This presents issues related to being rooted in one location. For example, if a tree were to grow near the camera, it would need to be chopped down or the entire system may need to be relocated.[28] With the lightweight and portable D6 allSky camera, relocation is not a difficult process.

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[23]I'd actually flesh this out more in its own paragraph for a nicer comparison to say the CAMS systems.

[24]Really most of the thermistat is there to *heat* the system to ensure it stays above the dew point.

[25]This bit doesn't really seem like it fits in "Composition"

[26]Should this be here or after you've talked about other systems? It might actually be better to discuss the background of fireballs and *then* discuss our setup.

[27]Very vague. Specific and reference examples would be better.

[28]A tree is a pretty slow growing thing so might not be the best example. What if a new building is erected nearby or a large cooling units is added to the roof of the building?

Figure 2.4: An entrenched alternative allSky camera.[Should expand on this. At glance this looks hardly different from ours, and maybe even smaller?]

Most importantly, the D6 AllSky camera is a less expensive alternative to other fireball analysis tools.[29] The ingenuity of running initial analysis on a microcomputer allows the D6 allSky camera to cost a fraction of what professional systems cost. Although large professional organizations produce copious amounts of wonderful data, in the field of fireball research, non-intensified systems outnumber intensified systems 2 : 1 [5]. [30] Providing a cost efficient alternative could be a great way to expand the field of fireball research and in turn provide a better understanding of the near-Earth objects in our solar system.

2.3   Photometry

After collecting videos of potential fireballs, next comes the task of analyzing the videos. Luke Russell, advised by Dr. Jed Rembold, wrote a photometry program in Python that allows us to get a calibrated light curve for a given video of a fireball. Simply running a fireball video through his interactive GUI allows us to access information about luminous properties of the fireball. However, limitations to our photometry must be taken into account. False positives, extinction, and other error factors must be accounted and corrected for while creating our fireball catalog.

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[29]If you are going to say most importantly, you better be able to back that up with hard numbers, which I'm not sure you can.

[30]What the heck does intensified and non-intensified mean in this context?!

2.3.1 Existing photometry tools

When running a video through the existing photometry script, the user must interact with the program.[31] After selecting a file to run through the program, the user must find the frame in the video which the fireball first becomes visible.[32] Then, the user must left click on the fireball. After this, the user must right click on a reference star with a known magnitude. This step requires a bit of knowledge and will hopefully be automated throughout this project. After selecting both of these and entering in the known magnitude of the reference star, the program will automatically track the fireball throughout the following frames. By using Gaussian fits to the photometric data, the program is able to center its view on the fireball and determine its size throughout its path. Throughout this process, the video also sums the photon counts for each fireball pixel for each frame. This photon count gives us the magnitude of the fireball at a given point in its path. Doing this for each frame results in a light curve that shows the magnitude as a function of time. By using relations given in the Analysis section[33], we are able to calibrate the magnitude and from that calculate the intensity which yield the valuable light curve. From this light curve, we can then move on to further analysis.

2.3.2 Planes, ~~Trains~~ Bugs, and ~~Automobiles~~ Extinction

Figure 2.5: An elusive fireball/raccoon hybrid.

While it is able to capture fireballs, the D6 allSky camera still picks up a great deal of false positives. In an initial sample of over 700 videos, only 2 of them contained real events. The vast majority of the videos were of bugs crawling across the acrylic dome. Because the bugs are illuminated by nearby light, they

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[31]Sure?

[32]This process seems spelled out in an overly detailed way here.

[33]If you are going to talk about them here, you can and should at least introduce the background behind them.

appear to be bright spots traveling across the screen and thus the detection script mistakenly flags them as fireball events. Moreover, many bugs are featured in several videos as they have a tendency to move, stop somewhere, and move again. While this is somewhat problematic, we aim to implement several steps to limit the number of false positive bug cases.[34]

In addition to bugs, other events such as airplanes, satellites, and Iridium flares provide false-positive videos. Their near-linear motion and bright presence are an instant trigger for the fireball detection. This is a more difficult bug to fix when compared to the bug bug :). These two cases are just small examples of false positives that result in difficult data to process.[35]
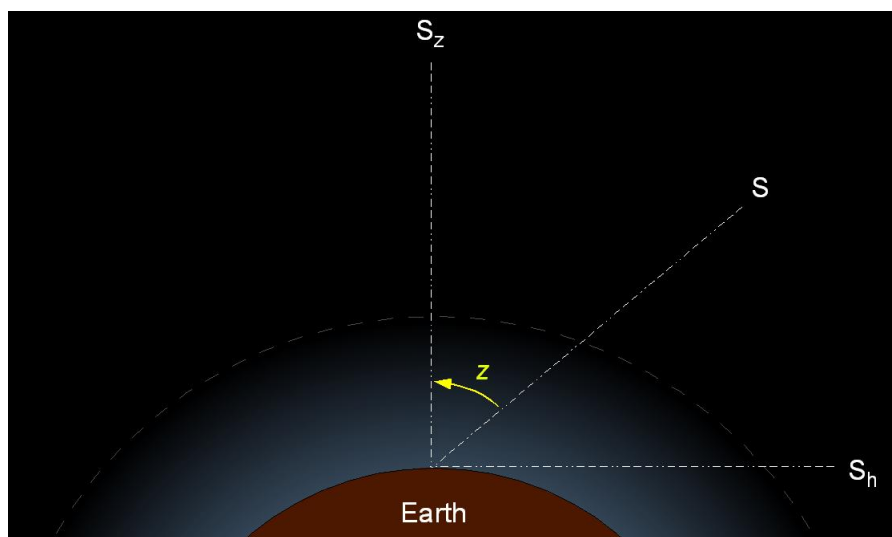

Figure 2.6: A depiction of atmospheric extinction.[This isn't really a depiction so much as a very rough diagram showing some direction. A depiction would be clear evidence of an object of constant brightness seeming dimmer near the horizon.]

A larger problem in data analysis stems from the phenomena of atmospheric extinction. As shown in Figure 2.6[36], we observe that when looking close to the horizon (S_h in the image), light must travel through a larger volume of atmosphere than it does for an observation close to the zenith (S_z in the image). Because the light travels through more atmosphere, more of the light is absorbed by gases or scattered by air particulates [1].[37] A prime example of atmospheric extinction is that of the Sun. When directly overhead, the Sun is at its brightest and one should never directly look into it. However, close to the horizon, the Sun appears

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[34]Should have talked about what those would be, but definitely should now!

[35]What two cases? The end of this paragraph is a bit disjointed

[36]references to an image should always come before the image

[37]Can we not find a better reference for this?

more red and can be looked at directly. Because a rising or setting Sun's rays must travel through more atmosphere, they are scattered due to this extinction and become more comfortably visible. Part of this project will include accounting for atmospheric extinction in a secondary photometric analysis script.[38]

2.4 Analysis

When creating the catalog, we must first recognize real events. After running the videos of those events through our photometry script, further efforts must be made to calculate properties such as luminous efficiency, total calibrated energy, velocity, and mass.

2.4.1 Parameters of Interest

When analyzing our fireball sample, we will make several key assumptions. Firstly, we assume the velocity of the fireball to be traveling at _____ meters per second. Because we do not have multiple cameras at different locations, we cannot confidently estimate the trajectory of the fireball in question. Although some may view this as sloppy, several other sources perform similar estimations and are able to consistent flux rates with other more well-recognized systems. Additionally, we will assume a luminous efficiency of _____.

Using these assumptions we can use the following equation:

$$m = \int \frac{2L}{\tau v^2} dt \tag{2.1}$$

where L is the luminosity, dt is the change in time, v is velocity, and tau is the luminous efficiency. This will give us a precise estimate for the initial mass of the object in question. Paired with our assumption that fireballs on average have a density of _____ and a generally spherical shape, we can calculate the diameter using the following equation:

$$d = 2(\frac{3m}{4\pi\rho})^{1/3} \tag{2.2}$$

where ρ represents the density of the fireball prior to entering the atmosphere.

In addition to calculating the mass and diameter of the fireball, we also aim to calculate the optical energy and total calibrated energy. These can be calculated using equations.

Insert energy equations here. I do not know where they exist.

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[38]What does this involve?

2.4.2 Flux

The most important data yield we hope to get is a flux consistent with that of other existing surveys. We hope to collect data that matches the following equation:

$$\log N = a_0 - b_0 \log E \tag{2.3}$$

where N is the total number of objects colliding with earth each year and E is the respective energy of the sample in kilotons [3]. In this equation, $a_0 = 0.5677 \pm 0.015$ while $b_0 = 0.90 \pm 0.03$. This relationship is known as a power law, as many professional AllSky systems' data match it well. The flux is dependent on three things: the number of events, the time of observation, and the area of the sky observed. The longer we use the system, the more precise, but not necessarily more consistent, our flux will be.

One factor that is particularly difficult to deal with when considering flux is the area of the sky that is being observed at a given time. Derived using basic trigonometry, we know

$$\text{Sky Coverage} = \Omega(h + r)^2 \tag{2.4}$$

where Ω is the steradian, or solid angle from earth, h is the height above Earth's surface, and r is the radius of Earth. The CCD fish-eye camera that we use spans approximately $140\,\text{deg}$. When assuming that the height of the fireball is approximately 75km from Earth's surface, we learn that our camera covers about $119,000\text{km}^2$. That area translates to about 0.023 percent of Earth's total surface. This fact solidifies the importance of many fireball camera systems, as an individual only covers a small fraction of Earth's total surface area.

One might naively assume that the total observation area would remain consistent each night. However, one must consider clouds and fog when calculating the overall sky area covered. This consideration will be dealt with in our secondary analysis and is further discussed in the methods section.

2.5 Existing Surveys

While amateur astronomers and low-budget systems capture useful information, larger professional systems act as a vitally important comparison point. Individual events captured by an observer do contribute to the pursuit of knowledge. However, a small camera system that cannot yield similar data to more professional surveys serves only a marginal amount of utility. Cameras for AllSky Meteor Surveillance (CAMS), the SPanish Meteor Network (SPMN), and the Lincoln Near Earth Asteroid Research (LINEAR) program are examples of well-established existing meteor observing surveys. All of these programs are continuously acquiring

data and adding their findings to existing databases. Nearly all of this data is widely available, and is available to the public online.

2.5.1 CAMS

Funded by NASA, Cameras for Allsky Meteor Surveillance (CAMS) aims to verify minor meteor showers and trace them back to their existing parent comets [6]. The project was created by Peter Jenniskens and is based in California. The CAMS network is spread across 3 different locations and consists of over 60 cameras. Each camera is has a relatively narrow field of view 30 deg. Although they individually cover a small area, multiple cameras overlapping in field of view contribute to a large sky coverage. CAMS uses powerful CCD cameras to detect extremely dim meteors (up to around +5 mag). By spreading their cameras across three separate locations, the CAMS research group can measure extremely precise trajectories of the incoming meteors. Similarly to the phenomena of trying to catch a baseball with only one eye open, confidently capturing a three dimensional trajectory of a fireball is extremely difficult when using only one camera. Consisting of 3 cameras located within 25 miles of one another, as seen in Fig. 2.7 the CAMS survey have a median trajectory error of 0.31 deg and a median speed error of 0.53 km/s [6].

Figure 2.7: The three CAMS network stations within a 50 mile radius.

Accurate trajectories are particularly useful in back-tracing the motion of the meteor's orbit. The CAMS team has reduced over 320,000 of these orbits [4]. In addition to calculating orbits, CAMS also uses their precise velocity measurements to draw relations between speed and other properties. Figure 2.8 shows the relationship between the apparent incident speed and peak magnitude.

Although the plot itself doesn't show a linear relationship, when considering the two subsets of relatively higher and lower incident speeds, we can see a general trend. That trend shows that lower incident speed meteors tend to have slightly dimmer peak magnitudes.
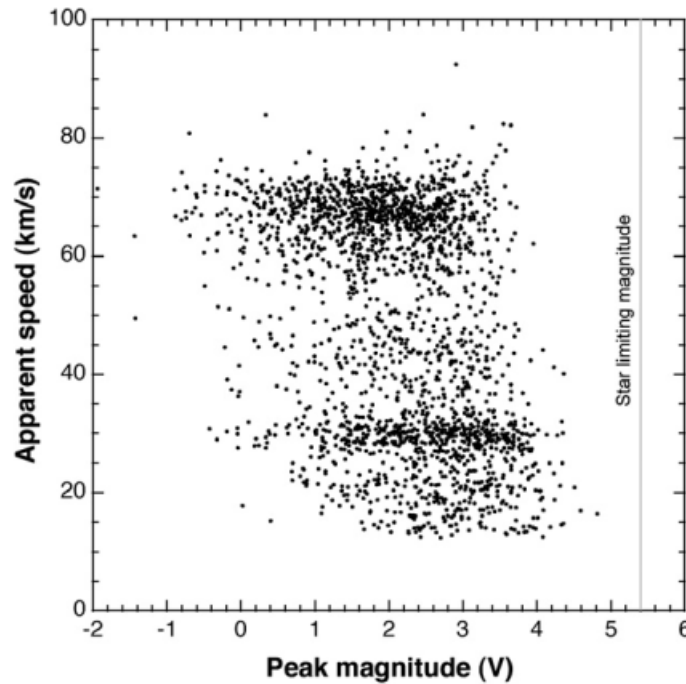
Figure 2.8: Relationship between incident apparent speed and peak magnitude for CAMS data taken in November of 2010 [6].

2.5.2   SPMN

The SPanish Meteor Network (SPMN) works extremely similarly to the CAMS project. It consists of 25 observation stations located across Portugal and Spain [11]. Figure 2.9 shows the approximate coverage of these stations along with some proposed locations (in green), from a satellite point of view.

In addition to becoming the first organization in Spain to successfully calculate the orbital path of a meteor, this organization revolutionized fireball research by developing the first CCD AllSky cameras [8]. These cameras are now in use all across the world. While the SPMN and CAMS are extremely powerful research organizations, their study of meteors only slightly overlaps with the research being discussed in this paper. Because of their high grade equipment, they are able to capture data from extremely dim sources. Fireballs, quantified by a magnitude below -4, compose only a small fraction of the meteors analyzed by these organizations. Fortunately, other organizations focus specifically on larger and brighter events.
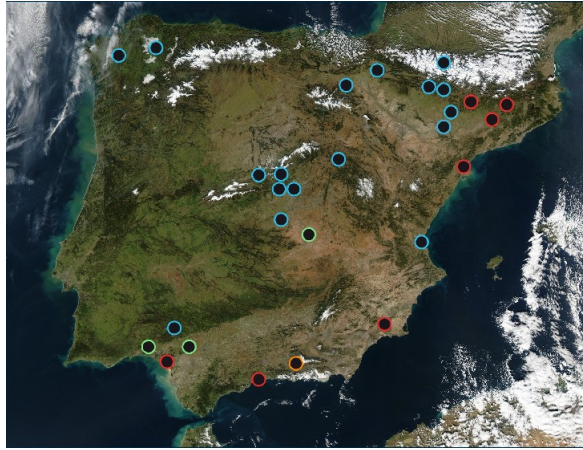
Figure 2.9: Satellite view of the SPanish Meteor Network's sky coverage across 25 existing and 3 proposed observation stations [8].

2.5.3 Other research groups

There are a multitude of ways that one can attain information about a fireball. All the aforementioned surveys have employed the use of photometric data. Peter Brown, a well renowned fireball researcher, took data from the Department of Defense and the Department of Energy space-based systems in geostationary orbits. The original purpose of these systems is to detect signatures of explosions near earth's surface, but occasionally pick up false positives in the form of bolides. Because the systems detect the amount of power released, scientists such as Peter Brown can approximate the fireball's energy. In a 2002 article published by *Nature*, Brown estimated the optical energies of around 300 bolides. From this data set and other existing data sets, Brown created Eq. 2.10, which relates bolide energy to the number of impacts on earth each year.

Figure 2.10 shows this relationship alongside data taken from many different research groups. In his research, Brown used existing assumptions (mentioned in the Analysis section) for the blackbody distribution and the velocity.
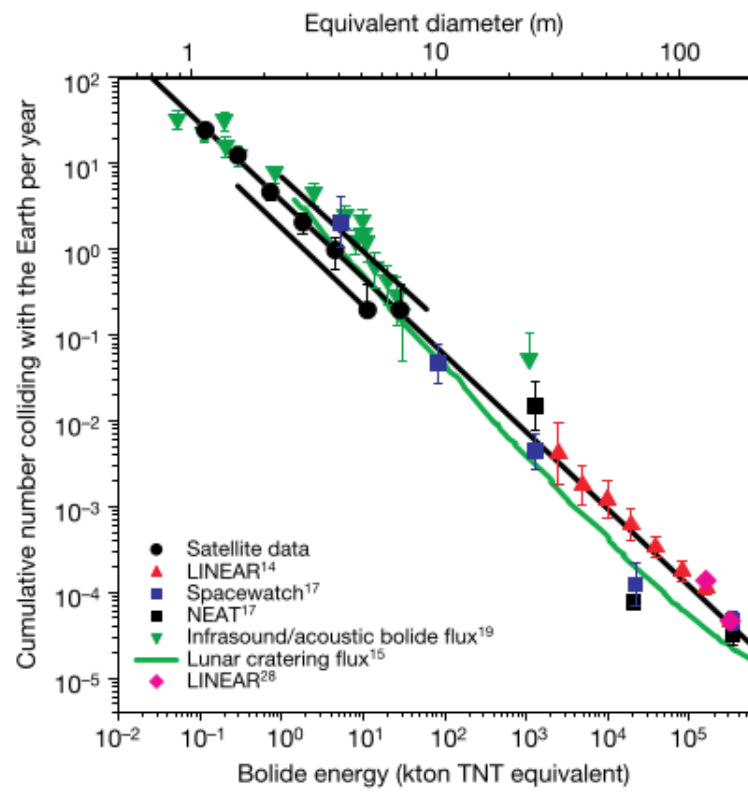
Figure 2.10: A plot of bolide flux using an conglomeration of data [3].

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[1] *Atmospheric Extinction - GAO*. URL: https://sites.google.com/site/gaobservatory/science/atmospheric-extinction (visited on 11/09/2018).

[2] Peter T Bobrowsky and Hans Rickman. "Comet/Asteroid Impacts and Human Society". In: (), p. 549.

[3] P Brown. "The flux of small near-Earth objects colliding with the Earth". In: 420 (Nov. 21, 2002), pp. 294–296.

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