Analysis of Light Pollution Spectra

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Abstract: Analysis of Light Pollution Spectra

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Light pollution is artificially-produced light which serves no useful purpose. It may be light directed toward places that do not need illumination or light that is directed directly into the sky. There are many different sources of light pollution. One way in which light pollution sources differ is their spectra—different light sources have different spectra and thus alter the night time sky glow in different ways. One can determine the proportions of light pollution produced by different light sources.

Spectra were taken in three directions: Baltimore, MD, Washington, DC, and Annapolis, MD. It should be noted that Laurel and Columbia, MD are in the same general direction as Baltimore and that Bowie, MD is in the same general direction as Annapolis, MD. Spectra of Washington were also taken both in the early evening and around midnight. Lines produced by sodium, mercury, scandium, thorium, lithium, oxygen, neon, and high-pressure sodium were detected. Sodium D lines and scandium lines were stronger in Baltimore than in any other city, suggesting that low pressure sodium and metal halide lamps are more prevalent there. Mercury and sodium lines increased over the course of the night, suggesting that the proportion of the sky glow produced by mercury vapor and high pressure sodium lamps increases over the course of the night. This study showed that the breakdown of light pollution spectra does change over the course of a night and that different cities do produce different sky glow spectra.

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Introduction to the Problem

Light pollution introduction. Many forms of pollution are associated with cities, including water, air, sound, and light pollution. Air and water pollution are usually regulated by local, state, and federal environmental agencies. Sound pollution is often regulated by local nuisance ordinances. However, light pollution is so regularly ignored that many people have never heard of it. Light pollution is a natural consequence of outdoor lighting. Streetlights are needed for traffic safety and crime prevention. Cars must have headlights. Nighttime sporting events need to be lit. Commercial signs and advertisements need to be lit if they are to be seen at night. Light that illuminates objects so they can be seen is essential if people are to be active at night. The problem is that much of the light goes to waste. Many lighting fixtures direct some of their light straight into the sky. Others shine all night even though they are not needed all the time. Such light does not serve any useful purpose and becomes light pollution.

There are several problems with wasting light. The most obvious is economic. Outdoor lights are powered by electricity and electricity costs money. If a city's streetlights direct a quarter of their light upwards, then a quarter of the money spent powering them is wasted. If this light was redirected downward, it would increase the effective brightness of the lamp. This would allow the use of a lower wattage bulb or fewer lamps and thus lower energy costs. Another problem is glare. Glare, or blinding light, occurs when lights shine directly into a person's eyes or when a bright light contrasts with unlit surroundings. In traffic, glare can be dangerous because it makes it very hard to make out details. For that matter, the glare caused by security lights that shine outward rather than down can actually aid criminals. Glare from a security light can make it difficult or impossible to see into darker shadows where a criminal may be lurking. However, there is a third reason that light pollution is bad. Light that shines upward illuminates the night sky. If Earth had no atmosphere, this light would be unimportant because it would shine straight into space. However, Earth does have an atmosphere and the atmosphere scatters back a significant portion of the light that is directed upward. This light pollution contributes to the sky glow and, in populated areas, often dominates it. Natural sources, such as auroras, zodiacal light, and starlight scattered by the atmosphere do contribute to sky glow, but, in urban areas, the vast majority of sky glow comes from light pollution (Foster, 2001). Even minor light pollution causes excess sky glow that affects professional astronomers. This is one reason why cities like Tucson, Arizona that are located near major observatories pay particularly close attention to sky glow and regulate the use of outdoor lighting. Tucson and other Arizona cities have shown that cities can efficiently and cost-effectively provide outdoor lighting necessary for public safety and commerce while minimizing light pollution (Eakin, 1986). Many of the objects studied by professional astronomers are very dim, and even relatively dim light pollution can produce enough sky glow to outshine these objects. However, in most American cities, light pollution has gotten completely out of control and the sky glow makes it impossible to see the Milky Way or recognize many of the constellations. Inside or near a major city, one can easily count the visible stars because most of the dim ones are drowned out by the sky glow (Foster, 2001). A fourth reason that light pollution is bad is that, by making the night brighter, it can interfere with the circadian rhythms of animals.

Differences between light sources. There are several types of lamps used to supply street and parking lot lighting. Incandescent lights are rarely used today except in cars headlamps and residential lights because they are inefficient—a glowing filament emits much of its light in the infrared part of the spectrum. In the past, virtually all street lamps were mercury vapor (HgV) lamps. They run a current through mercury gas, causing electrons to jump to higher energy levels. As the electrons fall back to the ground state, they release light of specific wavelengths, creating spectral lines associated with mercury. Specifically, HgV lights emit spectral lines at 5769 Å, 5790 Å, 5461Å, 4047 Å, and 4358 Å (Massey, Gronwall, & Pilachowski, 1990) These lamps are more efficient than incandescent lights (International Dark-Sky Association, 1996), but still emit much of their light in the ultraviolet and are the worst contributors to light pollution in the blue end of the spectrum. HgV lights are rarely installed in new lighting fixtures because they are less efficient then the newer sodium and metal halide lights, but they are still common because in the past the vast majority of outdoor lights were HgV. The most efficient light sources are low pressure sodium (LPS) lamps (International Dark-Sky Association, 1996). They operate on the same principle as HgV, but use sodium gas instead of mercury vapor. Because they emit nearly all of their light in a characteristic yellow spectral line pair with wavelengths of 5896 and 5890 Å, they do not waste energy emitting nonvisible photons. These are the best lights from an astronomer's point of view because they do not pollute very much of the visible light spectrum—only these two wavelengths are affected—and so can be easily filtered out (Massey, Gronwall, & Pilachowski, 1990). However, because they emit light at only two wavelengths, a scene illuminated by LPS lights is perceived as having no color and many people find this yellow monochrome lighting unpleasant. For this reason, many localities use high pressure sodium (HPS) lights instead. By pressurizing the sodium gas, they distort the sodium atoms' electron shells so that energized electrons do not always return to the atom they came from. This produces a light across a wider part of the spectrum. Although HPS lights require more electricity to produce the same amount of light (International Dark-Sky Association, 1996) and need to be placed more closely than LPS lights, HPS bulbs are cheaper and provide better color rendition, factors that many public works departments consider to be important. Astronomers consider them more problematic than LPS lighting because they are not monochromatic, but they are better than metal halide (MH) lights (Osterbrock et al, 1976). Due to the yellow tinge of their light, many HPS lamps have been replaced with MH lamps, which operate on the same basic principal as HgV lamps but which use various metal halide compounds as well as mercury in order to achieve a light that is perceived as white by the human eye. However, they are less efficient than HPS or LPS lights (International Dark-Sky Association, 1996). Furthermore, they are even more problematic for astronomers than HPS lights because the ingredients and mixture depend on the manufacturer, making it impossible to predict their spectra. While LPS lights are superior from the point of view of efficiency and minimizing light pollution, MH lights provide better color rendition and are often preferred by the general public. HgV lights are obsolete and are rarely installed new because of their low efficiency. The light source most commonly installed today for use as street and parking lot lighting is HPS lights because they serve as a trade off between LPS and MH lights.

Street and parking lot lights are not the only contributors to light pollution; other light sources illuminate cities at night. Car headlights and residential lighting are usually incandescent lights. The halogen headlights found in some cars are actually a form of incandescent light. Halogen lights consist of a tungsten filament surrounded by a halogen gas inside a quartz envelope. In all incandescent lamps, the tungsten in the filament slowly evaporates until it breaks. However, the halogen gas in halogen lamps reacts with the tungsten vapor and redeposits it onto the filament, allowing the filament to be run brighter and longer than in a normal incandescent lamp. Unlike HgV, sodium, and MH lights, incandescent and halogen lights emit a continuous spectrum without emission lines. Office buildings usually have fluorescent lighting and many people are replacing incandescent lights in their homes with small fluorescent bulbs. Fluorescent lights are essentially HgV lights that have been coated to spread out the mercury spectrum to produce a "whiter" light. Phosphor coatings on the bulbs absorb and re-emit light at different wavelengths, producing a light source with a higher continuum and less pronounced spectral lines than a normal HgV lamp. Most importantly, they absorb light from the main mercury line, which, at 2536 Å, is located in the ultraviolet, and re-emit it in the visible part of the spectrum. Light pollution from fluorescent lights, if it is a significant contributor to sky glow, would be bad for astronomers because, like incandescent lights, they are effectively continuous-spectrum (Sperling, 1986). Another source of outdoor lighting is neon signs. Neon signs run a current through a mixture of mercury and a combination of noble gases (neon, argon, krypton, or xenon) depending on the color desired, to produce light bulbs that can be shaped into words. These bulbs are often coated with phosphors, as in fluorescent lights. These bulbs usually produce a spectrum containing lines from the spectra of the elements used in them as well as continuum features from the phosphors.

Statement of the Problem

It is rare for a large urban area to be dominated by only one type of lighting. Parking lot lights and security lights may differ from the local streetlights. Car dealerships and other locations that require good color contrast are likely to use MH lights even if the local streetlights are more efficient sodium lamps. Older light fixtures are often still equipped with HgV lighting while newer ones usually use more efficient lamps. For that matter, commercial neon signs, incandescent residential lights and car headlights, fluorescent lights in office buildings, and other diverse light sources contribute to light pollution. In order to determine the actual contribution to light pollution of each type of lighting in a city, one must take a spectrum of the sky glow and decompose it into the spectra of its various constituents: fluorescent, neon, LPS, HPS, HgV, MH, and incandescent lights. It would also be interesting to determine if the breakdown in light pollution sources depends significantly on which city is viewed (due to different urban environments) and on what time of night spectra are taken (due to commercial lights being turned off and decreased vehicular traffic after a certain time of night). To determine this, spectra will be taken of the sky glow in the directions of Washington, DC; Baltimore, Laurel, and Columbia, MD; and Bowie and Annapolis, MD. Spectra will be taken of Washington, DC both in the early evening and around midnight. Spectra will also be taken of light from fluorescent, incandescent, LPS, HPS, HgV, and MH lamps. These spectra will be taken in the field with a portable spectrometer. Spectra will be collected of multiple lights of each type with the hope of obtaining spectra of several brands of each type of light. If possible, spectra of lights of each type will also be obtained from the manufacturers whose lights are most commonly used in the area.

Hypothesis

If the local cities are viewed at the proposed times, Laurel and Columbia and Bowie and Annapolis will have a lower percentage of their light pollution supplied by neon (commercial) and MH/LPS/HPS/HgV (street lamp) lighting because these cities are not as commercially developed as Baltimore and Washington, DC. If the components of the sky glow are compared at the proposed times, the contribution from incandescent / halogen and neon lights will decrease over the course of the night as vehicular traffic decreases and commercial lights are shut off. If average components are studied, HgV, HPS, and MH lights in the form of street and parking lot lights will dominate with minor contributions from incandescent / halogen, LPS, and fluorescent lights.

Variables and Limitations

Independent variables: time of night and direction of telescope when each spectrum is taken

Dependent variable: spectral intensity as a function of wavelength

Regulated Conditions:

1.) Wavelength dispersion calibrations will be performed.
2.) Standard star observation will be performed to allow for wavelength sensitivity calibration.
3.) Altitude of observations will be held constant.
4.) Azimuths will remain constant for all observations of the same city.
5.) All observations will be made from the same 36” Cassigrain reflector at the Goddard Geophysical and Astronomical Observatory (GGAO),

near the USDA Beltsville Agricultural Research Center.

Limitations:

1.) Properties of the telescope mount may make it necessary to point the telescope at a higher altitude than one might prefer or towards azimuths other than those of the city centers. This is primarily true of the northerly direction as one is not permitted to look beneath the pole star, Polaris. There is some uncertainty as to whether or not it will be possible to conduct the Laurel and Columbia observations at a different azimuth than the Baltimore observations

2.) Difficulty in obtaining pure spectra of the exact types of lamps used in local lighting may make it difficult identify the sources of some spectral lines. This is especially likely to be relevant with MH lamps because their ingredients differ significantly depending on manufacturer. Field sources may differ from the most common commercial light sources.

3.) Scattering geometry between light source and viewer can vary due to atmospheric conditions.

4.) Reflectivity of scattered light can depend on wavelength and angle of reflection.

5.) Due to time constraints, it may not be possible to obtain multiple spectra of more than one city or to obtain multiple spectra for any city at the same time of night.

Assumptions:

1.) Differences in humidity and presence of clouds will not affect the spectrum of the sky glow; they will only affect its brightness.

2.) Minor differences in the time of observation will not have a significant effect on the spectrum of the sky glow.

3.) Spectrograph and portable spectrometer provide accurate spectra once dark-current has been subtracted, and spectra have been wavelength-dispersion and intensity calibrated as a function of wavelength.

Statistical Analysis

Several types of statistical analysis will be performed. First, median filtering will be used and means and standard deviations will be found, both to improve the signal-to-noise ratio and to identify bad pixels which may be due to cosmic ray hits or excessive dark current. This will help eliminate the effects of non-statistical variations in specific observations. Second, polynomial regressions will be performed to determine a wavelength dispersion solution. Finally, nonlinear spectral fitting will also be performed to determine the different components and wavelengths of spectral lines that are too blended to identify visually.

Glossary

1.) Å (Angstroms) – One Å is equal to .1 nm or 1×10^{-10} m. In spectrometry, spectral lines in the visible part of the spectrum are often referred to by their wavelengths in Å.

2.) Airglow – Airglow is the component of the sky glow that is produced by natural sources in the Earth's atmosphere. The most spectacular demonstrations of airglow are aurorae, but there is always a certain amount of airglow.

2.) Altitude [angle] – See elevation.

3.) Azimuth – One way to identify a location on the sky is by its elevation and azimuth. Azimuth is the horizontal direction one looks too find a location in the sky, defined in degrees clockwise with 0º due north.

4.) Dark Current – A detector may produce a current due to thermal emission within the detector and thus register a signal in some pixels even if no light it present. This is called dark current. Dark current is removed from an image by taking an image with the lens cap on and subtracting it from an image taken with the same device with equal exposure time.

5.) Declination – One way to identify a location on the sky is by its declination and hour angle. The declination of a point on the sky is defined as its angular distance above or below the celestial equator, an imaginary line in the sky that runs directly above Earth's equator.

6.) Elevation [angle] – One way to identify a location on the sky is by its elevation (also called altitude) and azimuth. Elevation is defined as the angular distance above the horizon of a point in the sky.

7.) Flat-Field Correction – Not every pixel in a digital light imager (such as a spectrograph) has the same sensitivity. To correct for this, an image is taken of a field of constant brightness (a flat field) and the relative sensitivity of each pixel is determined and divided into the actual object image.

8.) Fluorescent Lights – Fluorescent lights are HgV lights that have been coated with a phosphor to flatten out the mercury spectrum by converting UV photos to visible photons with wavelengths in the empty parts of the spectrum. This produces a whiter light. They are often used in office buildings and are found in some residential lighting.

9.) Halogen Lights – Halogen lights are incandescent lamps in which the filament is surrounded by a quartz envelope containing halogen gases. Halogen lights can be run brighter and longer than normal incandescent lights because the halogen gas reacts with tungsten evaporated off the filament to redeposit it on the filament.

10.) Hour Angle – Hour angle is used along with declination to identify a specific elevation and azimuth as viewed from a specific location. When converted to time units, the hour angle of a location in the sky is the amount of time elapsed since a star at that point was above the observer's meridian (if the angle is positive) or the amount of time left to elapse until a star at that point will be above the observer's meridian (if the angle is negative).

11.) HgV (Hg Vapor) – Mercury vapor lamps run electric current through mercury vapor to produce a purplish light with the spectral lines of mercury. They were once commonly used as streetlights, but they have been made obsolete by more efficient sodium and metal halide lights. Many are still in use today.

12.) HPS (High Pressure Sodium) – High pressure sodium lamps run a current through highly compressed sodium gas. The atoms are so tightly compressed that they begin to act like a liquid and energized electrons from one atom may return to the ground state in another atom. This spreads out the sodium spectral lines into a partial continuum and produces a less severe yellow tinge than LPS lights.

13) IDL (Interactive Data Language – Interactive Data Language is a high-level computer language with a large number of specialized routines used to work with data arrays.

14.) LPS (Low Pressure Sodium) – Low pressure sodium lamps run a current through sodium gas at about 1 atmosphere to produce a monochromatic yellow light in the form of a spectral doublet at 5896 and 5890 Å. They are the most efficient lights and the ones most preferred by astronomers.

15.) MH (Metal Halide) – Metal halide lights contain a mixture of metal-halogen compounds. They operate on the same principle as HgV lights, but, depending on the ingredients and mixture, they produce many different spectral patterns. They are less efficient than sodium lights, but are sometimes used as streetlights or parking lot lights because they appear whiter than HgV or sodium lights.

16.) Neon Lights – Neon lights use noble gases and mercury to produce colored lights in long bulbs that can be shaped to order. They operate on the same principle as HgV bulbs and thus have the spectra of the gases used in them combine with phosphor continuum features.

17.) Sky Glow – Sky glow is the background light of the sky; the brightness of parts of the sky in which no specific light source is present. In nature, it is produced by reactions in the upper atmosphere, zodiacal light, and dispersed light from natural sources. However, in many urban areas today, the vast majority of the sky glow comes from reflected light pollution.

18.) Seeing – Seeing is a term used to describe the effect of the atmosphere on the resolvability of astronomical objects. Good seeing means that the air is very stable and that it does not significantly interfere with astronomy. Bad seeing means that pockets of air with different densities and other atmospheric conditions causes objects to twinkle and lowers the maximum achievable resolution.

19.) Wavelength Dispersion – Wavelength dispersion is the derivative of wavelength in terms of distance along the spectrum. It is measured in Å per pixel.

20.) Zenith – The zenith is the point in the sky directly above an observer, it has an altitude of 90º, an hour angle of 0º, and a declination equal to the observer's latitude.

21.) Zenith Angle – The zenith angle of a point on the sky is its angular distance from the zenith; the sum of the zenith angle and the elevation angle is 90º.

Chapter Two

The Review of the Related Literature

Introduction

Sky glow has both natural and artificial components. The natural components of sky glow are less location sensitive—while altitude may affect the observed airglow, location should have few other significant effects on the natural sky glow. One exception to this is aurorae, the frequency and intensity of which vary with latitude. It is worth noting, also, that time may influence the sky glow—the angle sunlight makes with the atmosphere may mean that different amounts of sunlight are bent around the horizon at different times of night, higher levels of the atmosphere see sunlight longer after dusk and sooner before dawn than the surface does, and, in any case, aurorae are dependent on the conditions of the Earth's magnetosphere. Artificial sky glow caused by light pollution, on the other hand, is very location-sensitive. In the few completely uninhabited areas of Earth, such as parts of inland Antarctica, there is no artificial sky glow. Osterbrock, Waters, Barlow, Slanger, and Cosby (2000) reported that at "dark sites", such as the Keck Observatory on the big island of Hawaii, artificial sky glow is negligible although detectable. On the other hand, Bortle (2001) reported that artificial sky glow was dominant in or near most heavily populated areas, and that, in inner cities, it was so great that all but the brightest stars were invisible. He also noted that, even in relatively dark suburban areas, artificial sky glow can decrease the limiting magnitude for the naked eye by about two magnitudes and decrease the limiting magnitude for telescopes even more.

The easiest way to distinguish between artificial and natural sky glow is spectrally. Atmospheric sky glow consists of many emission features; most are produced by O, O_2, OH, and other atmospheric constituents (Broadfoot & Kendall, 1968). The spectrum of the artificial sky glow is less definite because it varies depending on the types of lights being used in the area. Kaufmann (1981) noted that incandescent and halogen lights produced continuous spectra, but most of the more efficient light sources, such as florescent, HgV, HPS, LPS, and MH lights, had emission spectra that depended on the mixtures of gases in their discharge tubes and the phosphors used to change their color makeup. This artificial sky glow is the most problematic to astronomers, both because of its unpredictability and because of its growing brightness. The artificial sky glow caused by light pollution in major cities has already begun to brighten the sky at several major observatories, including Kitt Peak (Hoag, Schoening, & Couke, 1973 and Massey, Gronwall, & Pilachowski, 1990), Mt. Wilson (Sperling, 1986), and Mount Hamilton (Osterbrock & Martel, 1992), washing out dimmer objects. While spectroscopy can overcome some of the unpredictability of the artificial sky glow spectrum, artificial sky glow is nevertheless a serious problem for spectroscopy as it can overwhelm the spectra of objects one might wish to observe (Fletcher & Crampton, 1973).

The artificial sky glow has obvious effects on amateur and professional astronomers as well as on the general public. A brighter sky makes it hard or impossible to see many astronomical objects and both degrades the usefulness of established observatories and interferes with the hobby of amateur astronomy. It also drowns out many objects otherwise visible with the naked eye, destroying the beauty of the night sky for everyone. For example, Foster (2004) reported that 65% of the US population could not see the Milky Way from where they lived. Furthermore, the artificial sky glow also has significant detrimental environmental and economic effects. In 1991, Hunter and Crawford determined that 8.7 billion kilowatt-hours of electricity a year, equivalent to about 8.2 billion pounds of coal, were consumed merely to produce light that shines directly into the night sky—at a cost of 7.40 cents per kilowatt-hour, this cost over half a billion dollars a year. At the time, half of the electricity used in the United States was produced by burning coal, so the production of light pollution contributed to the air and water pollution that is associated with coal burning. Furthermore, the production of electricity by fossil fuel burning contributed to the production of greenhouse gases. Since coal burning is still a common source of electricity in the US, these environmental consequences still merit concern. The economic, environmental, and astronomical effects of light pollution can be remedied by using light fixtures that do not emit light upward and by using low-pressure sodium lamps wherever possible (Hunter and Crawford, 1991; Hunter and Goff, 1988; International Dark-Sky Association [IDA], 1996) . Low-pressure sodium lamps were found to be the most energy efficient type of lamp available for outdoor use (IDA, 1996) and Osterbrock, Walker, and Koski (1976) found that their relatively few emission lines did not contaminate the spectrum as badly as other types of lamps.

Another reason to consider light pollution is that artificial nighttime illumination can be detrimental to many species. The IDA (2002) reported that the attraction of insects to streetlights exposed them to an unnatural amount of predation and that sodium lamps (no distinction was made between HPS and LPS) attract significantly fewer moths than other types of lamps. The IDA also reported that the use of HgV lamps near waterways could affect the activity patterns of salmon and that the use of outdoor lights in general altered many predator-prey relationships. The IDA (1997) also reported that the New Jersey Light Pollution Study Commission found that light pollution was detrimental to birds. It was found that excessive outdoor lighting could diminish the feeding habitat of owls. The ability of outdoor lighting to alter the behavior of many wild animals is something that should be of concern to environmentalists.

This project studied the sources of light pollution through the analysis of the spectrum of the sky glow over several local cities at different times of night. It was necessary to determine which spectral features were the products of light pollution and which were natural sky glow features. Finally, it was important to know which light source or light sources were responsible for any particular spectral feature.

The Impact of Light Pollution on the Sky Glow

Light pollution as a function of population and distance. A brighter or nearer source would logically be expected to have a greater impact. However, since observations were conducted from a single fixed site, it was impossible to compensate for the differences in distances between cities by observing a single city from multiple distances. Furthermore, the cities used varied significantly in size. To account for these variations, several mathematical models of the effect of distance on a light pollution source's contribution to the sky glow were considered. Walker (1977) reported that the light output of a city is proportional to its population, assuming economic development is held constant. Walker also reported that the sky brightness due to the lights of a city is inversely proportional to the five-halves power of its distance. Garstang (1986) suggested that light output (L) as a function of population (P) might be more accurately determined by:

$$L = P(P/100000)^{1/10} \qquad (1)$$

However, he gave no experimental evidence to support this function. Treanor (1973) provided the following formula for the zenith sky brightness caused by a city X kilometers away with a population of P:

$$P((1.8/X) + (13.6/X^2))\exp(-.026X). \qquad (2)$$

Besides affecting the overall brightness of the sky glow, the distance from a light pollution source can also affect the relative brightness of different parts of the light pollution spectrum. Cinzano and Stagni (2000) reported that the artificial sky glow became redder the farther one is from a light pollution source and advanced a model for this color variation. This suggested that the blue spectral lines are being preferentially scattered more than the red spectral lines because of the distance of the source city. This effect would be expected to have been especially pronounced for the more distant cities, such as Baltimore.

<u>Light pollution as a function of elevation angle.</u> Due to time constraints, it was not considered practical to observe each city at a variety of elevation angles to determine at which angle the artificial component of the sky glow was greatest. Furthermore, the observation site was in a heavily light-polluted area and it would be difficult to determine if the artificial sky glow at a high elevation angle was due to a single city or a blending of cites. The 15º elevation angle was selected based on a study by Garstang (1986) which showed that the effect of a light pollution source on the sky glow brightness increased as elevation angle decreased and a study by Massey, Gronwall, and Pilachowski (1990) which showed that light pollution did not vary significantly as a function of azimuth at elevation angles of 60º or greater. To maximize the intensity of the observed light pollution spectral features and minimize the blending of light pollution from different

sources, it was considered preferable to observe at as low an elevation angle as possible. Since trees in the east made it impossible to observe and an angle lower than 15º, all observations used this elevation angle.

Natural Airglow Spectrum Features

In order to identify which spectral lines were the result of light pollution and which were natural components of the sky glow, it was necessary to be able to recognize natural airglow spectral features. Therefore, several studies of the visible airglow spectrum were consulted to identify possible or probable airglow features. The most comprehensive airglow study used was Broadfoot and Kendall's 1968 atlas of the airglow spectrum. This atlas consists of a complete spectrum with atmospheric lines identified covering the spectrum from 3,100 Å to 10,000 Å. Although some light pollution-produced Hg lines were present in the spectrum, they were identified by the authors as such and marked. Several other resources were also examined to identify possible airglow lines in the observed spectra. Osterbrock, Fulbright, Cosby, and Barlow (1998) discussed the locations and relative brightness of airglow lines produced by various isotropic variations of the hydroxide molecule. While it was relatively unlikely that these dim lines were detectable in the light-polluted sky glow at the observing site, it was important that it was possible to determine if they were present. Osterbrock, Waters, Barlow, Slanger, and Cosby (2000) detected other dim hydroxide lines that needed to be recognized as natural if found in the light-polluted sky glow spectrum. Slanger and Osterbrock (2000) also found lines corresponding to sodium and lithium in the natural airglow spectrum at Mauna Kea. This find was especially interesting because local governments reported that HPS lighting is very common in the observed areas (see pages

24-25 for details) and Osterbrock, Walker, and Koski (1976) found that HPS lamps emitted much of their light as sodium emission features. It was important to be able to distinguish between natural sodium airglow lines and sodium emission features from HPS or LPS lighting. Slanger and Osterbrock supplied frequencies and intensities for the sodium and lithium lines they found and it was necessary to compare this data with the observed sodium and lithium lines to determine whether the observed lines were likely due to light pollution or to natural airglow. Osterbrock, Walker, and Koski (1976) provided spectra of the Mount Hamilton sky glow with light pollution lines identified (all of the lines were produced by HgV lamps due to their almost complete dominance in outdoor lighting at the time of the observations). Massey, Gronwall, and Pilachowski (1990) also took sky glow spectra from Kitt Peak, in Tucson, Arizona, and identified light pollution lines in them.

Light Pollution Sources and Their Spectra

Obviously, in order to identify light pollution sources from their spectra, it is necessary to be able to recognize the spectra of all significant light-pollution sources in the observed area. It is best to use spectra of actual light pollution sources, such as were collected during the preliminary study. However, it is unlikely that every type of light pollution source was observed and, since the preliminary study was conducted in the field, it was still necessary to know enough about the spectra of different light sources to positively identify the light sources observed during the preliminary study.

Metal halide lamps. The gas mixtures (and thus the spectra) of metal halide lamps can vary greatly. According to Electrolink Magazine (2004), MH lamps in the US most often contain argon, mercury, iodine, sodium, and scandium, although dysprosium and other rare earth metals were often used. Heraeus Amba, Ltd. (2004) also mentioned iron and gallium as light emitters in their lamps. Kaufmann (1981) reported the use of sodium, scandium, thallium, indium, tin, and dysprosium iodides as well as mercury and argon in MH lamps. He also noted that while sodium, thallium, and indium typically produced only one emission line or closely spaced doublet in each in these lamps, at 589 nm (doublet), 535 nm, and 435 nm respectively, scandium, thorium, and dysprosium produced multiline spectra and tin produced a continuous spectrum. Kaufmann also noted that some metal halide lamps used phosphors to modify their color (and thus alter their spectra), although he did not specify which phosphors were in common use. Although these sources supplied information on the elements whose spectral lines were most likely to be found in metal halide lamps, they provided little insight into how these elements affected the emission spectra of MH lamps. The NIST Atomic Spectra Database (National Institute of Standards and Technology, 2004) was used to identify spectral lines found in spectra both from the preliminary study and from the main observations. Other useful information on MH lamp spectra was supplied by Slanger, Cosby, Osterbrock, Stone, and Misch (2003). Specifically, they supplied high-resolution spectra and tables of thorium and scandium lines in the Mount Hamilton sky glow attributed to MH lamps.

Mercury vapor lamps. Lockwood, Floyd, and Thompson, (1991) identified the five most significant visible lines in the mercury spectrum as 405 nm, 436 nm, 546 nm, 577 nm, and 579 nm. Osterbrock, Walker, and Koski (1976) supplied spectra of the light-polluted sky glow at the Lick Observatory on Mount Hamilton and identified the frequencies of the mercury lines present in them. These spectra were particularly interesting because they were observed before high-pressure sodium lamps were common and thus most of the pollution visible in them is produced by HgV lamps. Thus, if this spectrum is compared to an atlas of the natural sky glow (Broadfoot and Kendall 1968), almost all of the differences should be the result of HgV light pollution. Osterbrock et al. also discussed the spectrum of a GE mercury vapor lamp. The authors noted that the blue and yellow parts of the lamp's spectrum contained mainly mercury emission lines while the red portion of the spectrum was dominated by features produced by a phosphor that the manufacturer identified as europium-doped yttrium phosphate. Massey, Gronwall, and Pilachowski (1990) also identified sky glow lines produced by HgV lamp light pollution and provided a lab spectrum of an HgV lamp while Slanger, Cosby, Osterbrock, Stone, and Misch (2003) supplied high-resolution spectra of Hg emission lines in the Mount Hamilton sky glow.

Sodium lamps. Fletcher and Crampton (1973) took spectra of a HPS lamp to determine how their introduction was likely to contribute to the artificial sky glow spectrum. They found that the sodium lines produced by HPS lamps were an order of magnitude weaker than the mercury lines produced by HgV lamps of equivalent light output. They also reported line-strength ratios of 21:14:13 for the sodium lines at 3650, 3655, and 3663 Å and 1:3:39 for the sodium lines at 4339, 4347, and 4358 Å. Comparing these ratios to the line-strength ratios in the sky glow spectrum was useful in determining if HPS lights were the main source of sodium lines in the sky glow. Furthermore, Fletcher and Crampton (1973) noted that the Na I D lines are represented in the HPS lamp spectrum by a very wide emission feature with a 35 Å wide absorption feature in its center. Osterbrock, Walker, and Koski (1976) also discussed HPS lamps in their paper on the spectrum of light pollution at the Lick Observatory on Mount

Hamilton. While they found little evidence of sodium-lamp light pollution in the Mount Hamilton sky glow, they did take spectra of a Norelco LPS lamp and a General Electric HPS lamp. They published these spectra and noted several interesting features in them. Osterbrock et al. (1976) reported that nearly all of the light emitted by the LPS lamp was in the Na I D lines and the far red Na I 3^2P-3^2D $\lambda 8183$ and $\lambda 8195$ lines. They also labeled other sodium lines and lines produced by potassium and argon on the LPS spectrum. They reported that the HPS spectrum is dominated by the broad feature representing the Na I D lines, but stated that its central absorption feature was about 100 Å wide. Osterbrock et al. (1976) also noted the presence of other sodium lines and of K I, Sr I, and Hg I lines in the HPS lamp spectrum. Massey, Gronwall, and Pilachowski (1990) took spectra of HPS and LPS lamps as part of their study of the sky glow spectrum at the Kitt Peak National Observatory. They published these low-resolution spectra with the locations and wavelengths of various sodium lines marked. Their paper was also of interest because it provided some sky glow spectra with sodium lines marked and a table listing the wavelengths of sky glow lines attributed to HPS and, in one case, LPS lamps. Another study of the sky glow spectrum with respect to light pollution was performed by Slanger, Cosby, Osterbrock, Stone, and Misch (2003) at the Lick Observatory. They identified Li I lines in the sky glow spectrum, which they believed were produced by impurities in the gas mixtures of HPS lamps. They also identified Na I lines in high-resolution sky glow spectra. Kaufmann (1981) mentioned the presence of mercury and xenon in the arc tubes of many HPS lamps. He also noted the presence of noble gases in the arc tubes of LPS lamps and reported that nearly all of their light was emitted in two lines in the yellow region of the spectrum at 5890 Å and 5896 Å. The NIST Atomic Spectra Database (National Institute of Standards and Technology, 2004) was of use in identifying minor sodium lines present in the sky glow spectrum that were not mentioned in the astronomical literature.

Other lamps. Incandescent and halogen lights are continuous-spectrum emitters (Kaufmann, 1981) and thus cannot be identified by features in the sky glow spectrum Slanger, Cosby, Osterbrock, Stone, and Misch (2003) provided high-resolution sky glow spectra showing Ne I lines along with a table showing the wavelengths of Ne I lines that they detected in the sky glow and attributed to light pollution. It was assumed that these lines were the product of neon lights used in advertising. The NIST Atomic Spectra Database (National Institute of Standards and Technology, 2004) was of use in identifying sky glow features produced by other noble gases used in advertising signs. Fluorescent lamps in office buildings may also contribute somewhat to light pollution, however, no studies were found that discussed their spectra and the use of phosphors to distort the basic mercury spectra produced by the fluorescent tube. Furthermore, the use of phosphors made it difficult to predict where fluorescent lamps' emission lines should have occurred. Instead, field spectra of fluorescent lamps from the preliminary study were used to identify fluorescent lamp spectral features in the observed sky glow spectra.

Information on the Types of Lights in Use Locally

Some knowledge of the types of lights used as streetlights in the observed cities was considered useful since streetlights were expected to be major sources of light pollution, so various local governments were contacted and asked about their street lighting policies. Daniel Consultants, Inc. (2004) noted that the Washington, DC primarily used HPS lamps for its street lighting needs, although some HgV lamps were still in use and fluorescent lamps were used to light underpasses. They also noted that only MH lamps were used in the District's "monumental core" around the Capitol, White House, Tidal Basin, and National Mall. Daniel Consultants, Inc. also indicated that HPS lighting was used on all state roads in Maryland. Andre Issayans of the Prince George's County Department of Public Works and Transportation (2004, private communication) indicated that Prince George's county (where Bowie, Laurel, and the observatory are located), used HPS lamps on county-maintained roads. James Henrikson, director of the Bowie Department of Public Works, (2004, private communication) reported that Bowie switched all of its streetlights from HgV to HPS lighting about ten years ago, but that the city did not use LPS lighting because of its extremely yellow color. He also noted that HPS lighting was often avoided in high-population areas because many people disliked its orange color. William Malone, chief of the Howard County Bureau of Highways (2004, private communication) reported that the county, where Columbia is located, was in the process of converting from HgV and LPS lighting to HPS lighting on county roads because the HPS lights were considered more efficient. Robert Couchenour, Acting Assistant to the Public Works Director of the City of Annapolis (2004, personal communication), stated that the city primarily used HPS lamps, but that some LPS and HgV lamps were also in use.

Summary

In order to conduct this study, four basic types of information were researched. Models of light pollution's effect on the sky glow as a function of time of night, elevation angle, distance from the source, and population of the source city were studied. This aided in the selection of observation times and directions and helped account for the differences in population and distance between the cities studied. Furthermore, the natural airglow spectrum was researched. In order to identify spectral features produced by light pollution sources, it was necessary to be able to recognize which spectral features were natural and not the product of light pollution. At least as important was information on the spectra of various light pollution sources. Spectra of HgV, LPS, and HPS lamps were obtained along with information on their major emission lines and night-sky spectra with pollution lines identified. Although it was impossible to find a spectrum of a MH lamp (and even if one was found, the spectra of MH lamps vary so much that it would be of limited use), information on the most commonly used elements in MH lamps along with their spectral lines was obtained. Information was also obtained on the spectra of other types of outdoor lighting. Finally, local agencies in charge of street lighting were contacted and asked about the types of lights used in their jurisdictions. This served two purposes—to serve as a back check and ensure that the observed spectra were in reasonable agreement with the types of light being used, and to aid in differentiating between private and public lighting selections. The variety of sources consulted supplied necessary information for this study to be performed accurately and usefully.

Chapter Three

Materials and Methods

Equipment / Materials

Observing site. All sky glow observations were made from the Goddard Geophysical and Astronomical Observatory (GGAO), located a few miles northeast of Eleanor Roosevelt High school at latitude 39.022º N and longitude 76.827º W. Sky glow over Washington, DC; Baltimore, MD; Laurel and Columbia, MD; and Bowie and Annapolis, MD were observed. Theses sites were chosen because of their high populations, urban natures, and proximity to the GGAO, which should make them major contributors to the sky glow as viewed from that site. Laurel and Columbia, MD and Bowie and Annapolis, MD were treated as single sites because they have such similar azimuths (see Table 3.1) that their contributions to the sky glow as viewed from the site were indistinguishable.

1.) 36-inch Boller and Chivens Cassigrain reflector telescope manufactured by Perkin-Elmer Corporation, South Pasadena, California (f-number = 13.5, plate scale = 16.7’’/mm) located at the GGAO (for use in sky glow observations)

2.) long-slit (25 mm slit length) Boller and Chivens spectrograph manufactured by Perkin-Elmer Corporation, South Pasadena, California that covered approximately 4000 Å to 7000 Å at moderate resolution, resolving power about 4 Å (for use in sky glow observations)

3.) CCD camera (detector) manufactured by Apogee Instruments, Auburn, California, with a CCD chip manufactured by E2V Technologies Elmsford, New York, controlled by a Dell Inspiron 4100 laptop computer (for use in sky glow observations)

4.) a portable spectrograph, controlled by a Dell Inspiron 4100 laptop computer, manufactured by Ocean Optics, Dunedin, Florida that covered approximately 3000 Å to 7000 Å with a resolving power of about 4 Å (for use in the field source observations)

5.) Interactive Data Language (IDL) programming language, manufactured by Research Systems, Inc., Boulder, Colorado (to analyze data, including produce graphs of spectra, make instrumental corrections such as eliminating noise and dark current, and calibrate for intensity and wavelength dispersion)

6.) a clock supplying time accurate to the second (used to determine the time and duration of the observations)

7.) The Astronomical Almanac for the Year 2002, published by the Nautical Almanac Office: United States Naval Observatory and Her Majesty's Nautical Almanac Office: Rutherford Appleton Laboratory (to find the exact coordinates of the GGAO)

8.) the website http://www.heavensabove.com, run by Heavens Above GmbH (to find the exact coordinates of the cities observed)

Methods

Preliminary study. As a preliminary study, spectra were taken of field location light sources. These sources were chosen to be representative of the types of light sources expected to be significant contributors to the light pollution from the cities studied. A computer-controlled fiber optic spectrograph was taken, by car, to various outdoor lighting sources in Greenbelt, MD, between 19:30 EST on the night of Saturday, February 5, 2005 and 01:00 EST on the morning of Sunday, February 6, 2005. Spectra were taken of halogen, neon, HPS, LPS, HgV, and MH lights. Spectra were also taken of fluorescent and incandescent lamps at Goddard Space Flight Center. Bias, dark current, and calibration lamp data were taken to allow for later calibration of the data. IDL was used to subtract off the bias and dark current. An IDL routine, polyfit, was used to determine the wavelength dispersion solution from the calibration lamp data. IDL was also used to produce final plots of the spectra. The data from the preliminary study were used to determine the light sources responsible for features of the sky glow spectrum. All observational and calibration data were processed in the same way as the data from the major observations (see below).

Procedures. The major observations were conducted with a moderate-resolution long-slit spectrometer attached to a 36-inch Cassigrain reflector telescope (hereafter referred to as “the telescope”) at the Goddard Geophysical and Astronomical Observatory (GGAO). The spectrometer was used to take spectra of the sky glow at a low elevation angle (15º) in three directions of the region of the spectrum between 4000 Å and 7000 Å. Three spectra were taken in each city’s direction and in the zenith direction for each of the three observation times. All observations were taken during the course of one night. At the end of the night, a spectrum was taken with the aperture covered to create an image of the dark current produced by the detector. This dark current image was to be subtracted from each sky observation to leave only that signal produced by sky glow. However, difficulties with the CCD detector (see Chapter 4) led to a different technique for determining the dark current, as discussed in Chapter 4.

Spectra were also taken of a mercury-argon calibration lamp that emitted light in known spectral lines for use in determining a wavelength dispersion fit. Also, spectra were taken of Rigel (β Ori) for intensity calibration, to assess sky conditions, and to determine the sensitivity of the detector as a function of wavelength. Spectra were taken in the directions of Washington, DC, Baltimore, Laurel, and Columbia, MD, and Bowie and Annapolis, MD. Spectra of Washington were taken both in the early evening and near midnight. To take a spectrum in a specific direction, the telescope was pointed at a predetermined azimuth for the city or cities to be observed (see Table 3.1). These azimuths were calculated with a spreadsheet using coordinates from the Heavens Above website and the 2002 Astronomical Almanac (see materials). In the calculations, it was assumed that the Earth is flat—a reasonable assumption considering the distances involved. The goal was to use the same elevation throughout the observations, pointing the telescope at a very low elevation since the effect of a city on the sky glow rapidly diminishes as elevation increases. This led to a difficulty with the northerly cities—one cannot usually point an equatorially mounted telescope under the pole star. However, the particular telescope used in this study could be pointed below the pole star if, and only if, the azimuth was due north. Therefore, the three northerly cities were treated as a single city, located due north. This was reasonable as the two smaller cities are located slightly west of north and, while Baltimore is more significantly east of north, suburban Baltimore stretches more to the west than to the east of the city center because the eastern edge of the city is bounded by water. Spectra were also taken in the zenith direction—in this case the telescope was pointed at an elevation of 90º and azimuth was irrelevant. All spectra were taken as a combination of two exposures, one with the spectrograph diffraction grating in the red position (4˚10') and one with the grating in the blue position (2˚45').

While weather and seeing are important in many types of astronomical observation, they are not as important here with the exceptions of actual precipitation and significant cloud cover. Observations could not take place on nights during which precipitation occurred or was predicted because, on these nights, the observatory roof had to remain closed to protect the instruments. No attempt was made to focus on any specific object other than the standard star. Since the intensity of spectral lines was measured in arbitrary units, the exact brightness of the star was irrelevant and seeing was thus relatively unimportant. Cloud cover was not considered detrimental since clouds reflect more light down than the atmosphere does, so they would only increase the intensity of the spectral lines studied. While cloud cover would reduce or eliminate the airglow spectral lines that would be observed on a clear night, these lines are irrelevant to the study other than that they must be differentiated from the sky glow lines produced by light pollution. Changing sky conditions do not affect the measurement of relative changes in the sky glow spectrum, but the better the sky conditions, the greater the likelihood of measuring absolute intensity variations.

Data collection and analysis. All spectra and images were taken with the long-slit spectrograph. Two types of data were collected, calibration images and spectra and actual sky glow spectra with their associated information. A dark current image was taken by recording the image reported by the spectrometer when its aperture was covered so no light could enter. However, problems with the detector, which are discussed in Chapter Four, made these images unusable and dark current was instead determined from the values of pixels in the part of the detector that the spectrograph did not project light on. The spectra of mercury-argon calibration lamps were recorded for later use in finding a wavelength dispersion solution. The telescope was pointed at a Rigel and spectra were taken to assess sky conditions and determine the sensitivity of the detector as a function of wavelength. Four pairs of red and blue spectra were taken of the cities along with two pairs of zenith spectra. For each spectrum, the altitude and azimuth were recorded along with the start and end times of the observation.

After data collection was complete, the observational data was processed. The first step of this processing involved the use of the calibration data to remove detector artifacts and develop a wavelength dispersion fit for the spectra. IDL was used to subtract off dark current and to remove cosmic ray hits and hot pixels. The spectra of the mercury-argon calibration lamp were then compared to published mercury spectra to determine the wavelength dispersion relationship for the spectrometer—that is to determine the wavelength as a function of pixel position. Polynomial regression was performed to determine this relationship based on the locations in the observed calibration lamp spectra of lines with known wavelengths. Once this was done, the observed spectrum of the standard star was compared with a published spectrum to determine how the sensitivity of the detector varied with wavelength. The ratio of the observed spectrum to the published spectrum was used to determine the variations in detector sensitivity as a function of wavelength.

Once the calibration of the spectra was complete, the sky glow spectra were analyzed to determine the sources of light pollution in the areas they represented at the times they were taken. The first step of this process was to identify the emission and absorption features of the airglow spectrum. The sky glow spectra were compared with published airglow spectra taken at dark sites to identify the airglow emission lines in the observed spectra. Once these lines were identified, it could be assumed that the remaining lines were caused by light pollution of one sort or another—however the source of the light pollution was not yet known. To determine the sources of the light pollution responsible for the non-airglow features in the observed sky glow spectra, it was necessary to identify the unknown lines in the spectra and then to determine the light sources that produced them. The lines were identified by examining published spectra of light-polluted sky glow spectra and databases of atomic, molecular, and ionic emission lines. Once the lines were identified, their sources were determined in two ways. First, the laboratory and field light source spectra, along with published light source spectra, were analyzed to determine which lines were present—lines in the sky glow spectra present in only certain types of light source were most likely the result of light pollution from that type of light source. Furthermore, published descriptions of the gases found in emission line lamps—neon, HgV, LPS, HPS, and MH—were examined to see if these lamps might contain the substances responsible for the emission lines. This last technique was particularly important for MH lamps because they are less common than the other types and there are so many gas mixtures used that it is highly improbable that our collection of light-source spectra contained all types of MH lamp.

Table 3.1

Observation Coordinates for Sky Glow Observations

City	Coordinates (Real and Observed)			
	Latitude and Longitude	Actual Azimuth	Observed Azimuth / Elevation	Hour Angle / Declination
Goddard Geophysical and Astronomical Observatory	39˚ 01' 12" N, 78˚ 49' 48" W	0˚	0˚ / 90˚	00:00 / 39˚ 01'
Washington, DC	38˚ 54' 00" N, 77˚ 02' 22" W	239˚	239˚ / 15˚	03:53 / −12˚ 54'
Baltimore, MD	39˚ 17' 24" N 76˚ 36' 47" W	39˚	0˚ / 15˚	12:00 / 66˚ 00'
Laurel, MD	38˚ 05' 56" N 76˚ 50' 56" W	344˚	0˚ / 15˚	12:00 / 66˚ 00'
Columbia, MD	39˚ 14' 24" N 76˚ 50' 24" W	357˚	0˚ / 15˚	12:00 / 66˚ 00'
Bowie, MD	39˚ 00' 25" N 76˚ 46' 44" W	107˚	102˚ / 15˚	−04:54 / 00˚ 24'
Annapolis, MD	38˚ 58' 41" N 76˚ 29' 35" W	98˚	102˚ / 15˚	−04:54 / 00˚ 24'

This table shows the coordinates of each of the cities observed and of the observing site (the Goddard Geophysical and Astronomical Observatory). It then shows the azimuth of each city as viewed from the observing site. These azimuths were calculated with the assumption of a flat Earth, a reasonable assumption considering the distances involved. These are followed by the azimuths and elevations at which observations were actually taken. These are then converted into hour angles and declinations, the astronomical coordinates actually used to point the telescope.

Chapter Four

Results

Data

General description. Due to constraints of the observing equipment, all spectra were taken in pairs with one spectrum covering the red end of the visible spectrum and the other covering the blue end of the visible spectrum. These pairs overlapped by approximately 800 Å. The DC 1 pair (HA: 3.88, Dec: –12.9°), taken from 8:13 PM to 8:41 PM local time, the Baltimore pair (HA: 12.0, Dec: 67.0°), taken from 9:45 PM to 10:09 PM local time, and the Annapolis pair (HA: −4.50, Dec: −5.00°), taken from 10:53 PM to 11:15 PM local time, cover the range from 3800 Å to 7500 Å. The DC 2 pair (HA: 3.88, Dec: –12.9°), taken from 12:02 AM to 12:25 AM, covers the range from 3400 Å to 7300 Å. The pairs have been combined into single, intensity-corrected spectra covering the range between 4300 Å and 7200 Å.

A group of spectra of light pollution spectra were taken during the preliminary study. They cover the range from 3500 Å to 7000 Å. Many, although not all, of their spectral features have been identified and they were used to help identify unknown features in the night-sky spectra.

Analysis of general properties. A visual inspection of the four pairs of spectra suggests that they are very similar. No major lines present in some of the spectra are absent from other spectra. For the most part, the shapes of the spectra appear very similar, a conclusion that is supported by the fact that when one is divided by another, the resulting plot is very flat with only a few large features that appear to be the result of imperfect alignment of the two spectra. One exception to this general similarity is the HPS emission-absorption feature centered around 5900 Å. In all spectra, this feature consists of a wide (about 500 Å) emission feature with a absorption feature superimposed over its center and an emission line (the sodium D lines at 5890 Å and 5896 Å) superimposed over the absorption feature. However, in the Annapolis, DC 1, and DC 2 spectra, the right lobe of the wide emission feature is the tallest while in the Baltimore spectrum, the sodium D emission line is slightly taller than the rightmost lobe and the leftmost lobe is significantly shorter than the other two. Another interesting property of the spectra is that no phosphor-produced features or clear incandescent continuum features are apparent in any of them. Visible continuum features ca be divided into the groups. Some of the far-red continuum may be due to incandescent lamps, but the main source of continuum in the red is the HPS emission-absorption feature, whose wings extend several hundred angstroms in each direction. In the far blue, there is a significant rise in the continuum, apparently produced by MH lamps.

Identification of spectral features. Since the DC 1 spectra are the most intense, and thus have the most intense lines, spectral features were identified by performing Gaussian line fits on the DC 1 spectra and then studying the residuals produced by subtracting this spectrum from the other spectra. Virtually all features were found in all four spectra. Ten lines or unresolved groups of lines produced by sodium, five produced by mercury, one produced by lithium, twenty-nine produced by scandium, seven produced by thorium, three produced by airglow oxygen, seven produced by neon, and five produced by an unknown element in MH lamps were identified. Also present were the sodium D lines superimposed on the HPS emission-absorption bump between 5800 Å and 6100 Å. An atmospheric absorption feature produced by molecular oxygen was also noted, the B-band between 6867 Å and 6884 Å.

Table 4.1 catalogs the emission lines identified in the sky glow spectra. The first column identifies the element that produces the observed emission line. The second column identifies the wavelength of the observed emission line. The wavelengths given on the table are from the NIST Atomic Spectra Database Version 2.0. The third column specifies which spectra contain the line. The fourth column identifies the label used to identify the line on the plots of the spectra that follow the data tables. Since these plots do not cover the full range of the raw data, some lines are not in the region covered by the plots, and no label given for them. While relative intensities have not been calculated for the spectral features, it can be noted that the most intense line in each spectrum is the mercury line at 4358.4 Å, the second most intense is the mercury line at 5460.7 Å, and the third most intense is the sodium line at 5688.2 Å. The region between 5800 Å and 6100 Å in each spectrum is dominated by an emission-absorption feature that appears to be the sodium D lines superimposed on a wide emission-absorption feature produced by the distorted sodium D lines in HPS lamps. In some cases, more than one wavelength is listed in the same box and with the same graph key. In these cases, while only one lines is visibly discernible, there is evidence from Gaussian fitting the lines that multiple lines of the same element are blended together to from that line. Ten sodium features were identified at 4324.6 Å, 4494.2 Å, 4668.6 Å, 4747.9 Å / 4751.8 Å, 4982.8 Å, 5153.4 Å, 5688.2 Å, 5890 Å / 5896.0 Å, 6154.2 Å, and 6160.7 Å. Five mercury features were identified at 4046.6 Å, 4358.4 Å, 5460.7 Å., 5769.6 Å, and 5790.7 Å. Three airglow oxygen features were found at 5577.3 Å, 6300.3 Å, and 6363.8 Å. One lithium feature was found at 6707.8 Å. Seven neon features were found, at 5520.6 Å, 6334.4 Å, 6401.1

Å / 6402.2 Å, 6506.5 Å, 6678.3 Å, 6929.5 Å (DC 1 only), and 7032.4 Å (not in Annapolis). Seven thorium features were identified, at 4335.3 Å, 5199.2 Å, 5231.2 Å, 5258.4 Å, 5327.0 Å, 5343.6 Å, and 7124.6 Å (DC 1 only). Twenty-nine scandium features were identified, at 4227.2 Å, 4246.1 Å, 4728.8 Å / 4729.2 Å, 4141.1 Å / 4743.8 Å, 4753.2 Å, 4779.4 Å, 5064.3 Å / 5070.2 Å, 5081.6 Å / 5083.7 Å / 5085.6 Å / 5087.0 Å, 5096.7 Å / 5099.2 Å / 5101.1 Å, 5107.4 Å / 5109.1 Å / 5112.9 Å / 5116.6 Å / 5116.7 Å5339.5 Å / 5343.0 Å, 5349.3 Å / 5349.7 Å, 5356.1 Å, 5375.4 Å, 5392.1 Å, 5446.3 Å / 5451.5 Å, 5482.0 Å / 5484.7 Å, 5514.2 Å / 5515.0 Å, 5671.8 Å, 5686.9 Å, 5700.2 Å, 5708.6 Å, 5711.8 Å / 5717.3 Å / 5724.1 Å, 6210.7 Å, 6259.0 Å, 6985.6 Å (Annapolis and Baltimore only), 7127.2 Å / 7127.8 Å (DC 1 only), 7428.9 Å (DC 1 only), and 7453.1 Å (DC 1 only). Five unknown features produced by MH lamps were identified at 6193 Å, 6240 Å, 6457 Å, and 6591 Å. These wavelengths are accurate to about 1 Å.

Following the tables are plots (Figures 4.1-4.3) of the spectra that show the DC 1, DC 2, Baltimore, and Annapolis spectra with identified lines marked and keyed to the tables. The spectra have been adjusted to have the same mean value and have been intensity corrected so that they have the same intensity scale throughout. The graphs cover only the range from 4300 Å to 7200 Å because this was the range of the intensity-corrected Rigel spectrum used to correct for the wavelength-sensitivity profile of the detector.

Following the plots of the spectra are plots (Figures 4.4-4.12) of the residual spectra produced by subtracting the the DC 1 spectrum from the Annapolis, Baltimore, and DC 2 spectra respectively. Variations in the residual spectra signal lines that have different shapes or intensities in the two spectra being compared or that are absent from one of the spectra. Those lines that are present in only some spectra are identified in

Table 4.1 as well as the above list of lines identified. Annapolis had a larger proportion of its sky glow produced by mercury lines than DC while scandium, thorium, and sodium lines were of about the same intensity but had slightly different shapes, suggesting different gas mixtures or pressures in HPS and MH lights and a greater percentage of HgV lights. Baltimore had the most different spectrum of the three cities. It had a significantly larger contribution from scandium and thorium lines and a larger contribution from mercury lines than DC. While sodium lines were not particularly more intense than in DC, they had different shapes and the sodium D lines had a significantly greater intensity than elsewhere—they reached above the top of the HPS emission-absorption feature. This is evidence that HgV lamps are somewhat more common and MH lamps significantly more common in Baltimore than in DC. Also, it suggests that either LPS lamps are more common in Baltimore and are responsible for the strong sodium D lines, or else that Baltimore uses lower pressure HPS lamps that emit some light at the D lines instead of producing an absorption feature in their place. The main difference between the early and late DC spectra was that sodium and mercury lines provided a larger contribution to the sky glow in the late spectrum. While several neon and scandium lines seemed to change in intensity, the majority did not and it seems likely that this, like the apparent change in the shape of many features, was due to errors introduced by the unusually large offset required to fit the late DC spectrum to the common wavelength scale. This offset made the wavelength-dependent sensitivity correction less accurate because it introduced uncertainty into the wavelength fit and also changed the wavelength-dependent sensitivity of the system as a whole.

Figures 4.13-4.18 are the spectra collected during the preliminary study. Figure 4.13 consists of two fluorescent lamp spectra. Both are dominated by mercury lines, but while one has a wide phosphor feature from 4000 Å to 7000 Å, the other has a narrower phosphor feature centered on 4900 Å and a cluster of unidentified lines between 5800 Å and 6300 Å. Figure 4.14 consists of two spectra of HgV lamps. Both are dominated by mercury lines, but one also contains what appear to be small phosphor features around 6000 Å. Figure 4.15 shows two HPS spectra with various sodium lines and the dominant HPS emission-absorption features marked and one LPS spectrum with the dominant sodium D line and the 5688.2 Å sodium line marked. Figure 4.16 shows spectra of car headlights and an incandescent desk lamp. The spectra consist of continuous-emission features across the whole visible range. Figure 4.17 shows spectra of three MH lamps with mercury, sodium, scandium, and lit lines marked. They also contain a unidentified cluster of lines in the red that at first glance appear to be neon lines, but which are not. Figure 4.18 shows spectra of red, green, and blue neon signs. The red neon sign spectrum contains only neon lines, as would be expected. The green neon sign spectrum is dominated by a phosphor feature centered on 5700 Å with strong mercury lines and minimal neon lines. The blue neon sign spectrum contains strong mercury lines, a wide phosphor feature from 3700 Å to 5900 Å, and neon lines.

Following the preliminary study spectra are two plots that were prepared as evidence of the burn-in problem with the detector (see “Additional Observations”). The first (Figure 4.19) shows the line profile of several spectra—that is, it shows the CCD image collapsed in the direction of the dispersion so that what one sees is a graph of the intensity of the spectrum as you go from the bottom to the top of the detector. This plot shows that the narrow Rigel spectrum burned into the detector and continued to be present in the following sky and dark images. The second (Figure 4.20) is a plot of three regions of a dark frame—one region containing burned-in calibration lamp spectra, one region containing a burned-in Rigel spectra, and one region in a dark part of the detector. This demonstrates that the calibration lamp spectrum and Rigel spectrum burned into the detector and appeared in the dark frame even though the shutter on the detector was closed when the dark frame image was taken.

Following the plots are two images. The first (Figure 4.21) is the negative of the raw CCD image from the blue DC 2 spectra. The random spots are cosmic ray hits, which were removed during data processing. The parallel lines that run across the middle of the frame are spectral lines while the single line that runs the length of the spectrum is a residual image produced by an earlier calibration spectrum taken of Rigel. The second (Figure 4.22) is a negative of what should be a dark frame, but which is contaminated by after-images of the spectra of Rigel (a thin bar across the detector) and of mercury-argon calibration lamps (a series of vertical bars half the height of the detector).

Calculations Performed to Obtain Results

While statistical tests are generally of little use in analyzing the data from a survey study such as this, some calculations and statistical techniques were used to turn the raw observations into usable data. First, to remove the dark current images from the spectra images, an average value was calculated for the intensities of the pixels in the parts of the CCD images where no light from the spectrometer should have been present. This average value was then subtracted from the whole image. To remove cosmic ray hits from the CCD images, they were processed by an IDL program written for this project. First, any pixels with intensities more than twice the maximum intensity of a median-filtered version of the image were replaced with the average of nearby pixels. Next, the images were median-filtered and the median-filtered images were subtracted from the unfiltered image to create a residual. Any pixels more than five standard deviations from the average intensity in the residual were removed and the new residual was added to the median-filtered image. This process, which removed pixels that were significantly brighter than their neighbors and thus likely to be cosmic ray hits, was repeated using four standard deviations. IDL routines were then used to rotate the images so that the spectral lines were perpendicular to the long edge of the image. Each row and column was then median filtered independently and combined to form a template that was subtracted from the rotated image to make a residual. Pixels in the residual six standard deviations above the average value were replaced with an average of their neighbors and the new residual was added to the template to form a new image. The images were then collapsed into spectra. The IDL code of the program written to remove dark current and cosmic rays and to collapse the images into spectra is included as an Appendix 1. A program that performed Gaussian line-fitting techniques was used to identify the pixel locations of features in the spectra of mercury-argon calibration lamps to determine an approximate wavelength-pixel relationship which was used to identify major features in the sky-glow spectra so that an exact wavelength-pixel relationship could be found for them. The spectra were then resampled to linearize their wavelength scales. The Gaussian line-fitting program was then used to determine the wavelengths of features in the sky glow spectra. These wavelengths were then compared to a NIST catalog and published lists of sky-glow spectral features to identify their sources.

In order to determine the relative contributions of different light pollution sources, it is necessary to have a wavelength-sensitivity fit for the detector. To this end, spectra of the star Rigel were taken at the same time as the sky glow spectra. Because they required such short exposure times (5 s as opposed to 600 s for the sky glow images) and because they are so bright, it was not necessary to remove cosmic ray hits from them. Instead, they simply had their dark current subtracted off and were collapsed into spectra. By comparing them to a Rigel spectrum with known wavelength scales, the wavelengths of their major features were determined and wavelength-pixel relationships were determined for the spectra. They were then resampled onto the same linearized wavelength scale.

To intensity-correct the sky glow spectra, the sky glow spectra, observed Rigel spectra, and a published intensity-corrected Rigel spectra were resampled onto the same scale. The intensity-corrected Rigel spectrum was then divided by the observed Rigel spectra and the resulting correction factor was be multiplied by sky glow spectra to produce intensity-corrected sky glow spectra. However, because the intensity-corrected Rigel spectrum had a range of only 4300 Å to 7200 Å, all intensity-corrected sky glow spectra were limited to this range.

To help identify features in the sky glow spectra, the field lamp spectra taken in the preliminary study were used. They had bias and dark current subtracted off and a wavelength scale was produced for them in the same was as one was for the sky glow spectra. An IDL procedure, combine (see Appendix 2), was then written to perform two tasks. First, it combined saturated and unsaturated spectra of the same lamp to produce a spectrum that was unsaturated but had higher resolution than the raw unsaturated spectra. Then it linearized the wavelength scale and resampled the spectra onto this new wavelength spectra. The same Gaussian line fitting program used on the sky glow spectra was then used to identify features in the field lamp spectra.

<u>Additional Observations</u>

One of the most important results to come out of this project so far is completely irrelevant to the hypothesis. When the CCD images of the spectra were examined, it was discovered that taking one spectrum burned a residual image into the detector that persisted during several more exposures. Fortunately, of sky-glow features, only the HPS sodium emission-absorption feature was intense enough to have any appreciable burn-in effect and it did not burn in brightly enough to cause any serious problems. The calibration spectra of Rigel also burned in, but since they only contaminated a small strip much less than the width of the night-sky spectra, they were not a serious problem. The mercury-argon calibration lamps, however, burned in and appeared as normal spectral lines, so they may well be responsible for unidentifiable lines in the night sky spectra. The discovery that the CCD detector had this problem was very important because the group from which the detector was borrowed had only recently purchased it and was unaware that it was producing these residual images. One of the advantages of modern solid state CCD detectors is that they are not supposed to have this problem, so it was quite unexpected. The problem was documented using the data collected for this project and the camera was sent back to the manufacturer to be replaced.

Data Analysis

The data collected in this study makes it possible to evaluate the hypotheses and also to draw other conclusions about the light pollution in the three cities.

The hypothesis that HPS and HgV, and MH lights would be the dominant sources of light pollution in all cities at all times is supported. The dominance of the HPS emission-absorption feature in the red part of the spectrum and of mercury lines above sodium, neon, scandium, and thorium lines supports the hypothesis that HPS and HgV lights are dominant since the distorted sodium D lines are found only in HPS spectra and the mercury lines would be more similar in intensity to other lines if they had a major source other than HgV lamps. The presence of many scandium and thorium lines and of an MH-produced continuum in the blue end of the spectra suggests that MH lamps are more important as sources light pollution than neon signs, fluorescent lamps, or continuous emission lamps. It is unclear how they compare to HgV and HPS lamps, though. One cannot evaluate the intensity of LPS lamps to other lamps because the only significant LPS feature, the sodium D lines, is superimposed on the HPS emission-absorption feature.

The hypothesis that the fraction of the light produced by MH, HPS, LPS, and HgV lamps would increase over time is partly supported. The HPS and HgV lines in the normalized DC 2 spectra are clearly stronger than those in the normalized DC 1 spectra, but the MH lines do not seem to change in intensity and the LPS sodium D lines do not seem to change in intensity, although this is hard to determine since they are superimposed over the HPS sodium D feature.

The hypothesis that Laurel and Columbia and Bowie and Annapolis would have a lower percentage of their light pollution supplied by neon (commercial) and MH/LPS/HPS/HgV (street lamp) lighting because these cities are not as commercially developed as Baltimore and Washington, DC is not supported. No comparison can be made between Baltimore and Laurel and Columbia because these cities were treated as though they were in the same direction during observation and individual spectra were not obtained for each city. As for the comparison between Washington and Bowie and Annapolis, the mercury lines seem stronger in Annapolis and there seems to be some offset between the scandium, thorium, and sodium lines in the DC 1 spectra and the same lines in the Annapolis spectra, suggesting that different brands of MH and sodium lights with different gas mixtures and pressures are used in these cities. Although it is not relevant to a consideration of the hypotheses, it was noted that the LPS sodium D line is much stronger in the Baltimore spectra than it is in the other spectra. It was impossible, however, to determine whether Baltimore, Laurel, Columbia, or some combination of these was responsible for this.

Table 4.1

Spectral Features Identified in Sky Glow Spectra

Element Responsible	Feature		
	Wavelength(s)	Spectra Containing	Key to Features in Figures
Sodium	4324.6 Å	all	Na 1
	4494.2 Å	all	Na 2
	4668.6 Å	all	Na 3
	4747.9 Å 4751.8 Å	all	Na 4
	4982.8 Å	all	Na 5
	5153.4 Å	all	Na 6
	5688.2 Å	all	Na 7
	5890.0 Å 5696.0 Å	all	Na D
	6154.2 Å	all	Na 8
	6160.7 Å	all	Na 9
Mercury	4046.6 Å	all	n/a
	4358.4 Å	all	Hg 1
	5460.7 Å	all	Hg 2
	5769.6 Å	all	Hg 3
	5790.7 Å	all	Hg 4
Oxygen	5577.3 Å	all	O 1
	6300.3 Å	all	O 2
	6363.8 Å	all	O 3
Lithium	6707.8 Å	all	Li 1
Neon	5520.6 Å	all	Ne 1

Table 4.1 Continued

Spectral Features Identified in Sky Glow Spectra

Element Responsible	Feature		
	Wavelength(s)	Spectra Containing	Key to Features in Figures
Neon	6334.4 Å	all	Ne 2
	6401.1 Å 6402.2 Å	all	Ne 3
	6506.5 Å	all	Ne 4
	6678.3 Å	all	Ne 5
	6929.5 Å	DC 1	Ne 6
	7032.4 Å	DC 1, DC 2, Baltimore	Ne 7
Thorium	4335.3 Å	all	Th 1
	5199.2 Å	all	Th 2
	5231.2 Å	all	Th 3
	5258.4 Å	all	Th 4
	5327.0 Å	all	Th 5
	5343.6 Å	all	Th 6
	7124.6 Å	DC 1	Th 7
Scandium	4227.2 Å	all	n/a
	4246.1 Å	all	n/a
	4728.8 Å 4729.2 Å	all	Sc 1
	4741.1 Å 4743.8 Å	all	Sc 2
	4753.2 Å	all	Sc 3
	4779.4 Å	all	Sc 4

Table 4.1 Continued

Spectral Features Identified in Sky Glow Spectra

Element Responsible	Feature		
	Wavelength(s)	Spectra Containing	Key to Features in Figures
Scandium	5064.3 Å 5070.2 Å	all	Sc 5
	5081.6 Å 5083.7 Å 5085.6 Å 5087.0 Å	all	Sc 6
	5096.7 Å 5099.2 Å 5101.1 Å	all	Sc 7
	5107.4 Å 5109.1 Å 5112.9 Å 5116.6 Å 5116.7 Å	all	Sc 8
	5339.5 Å 5343.0 Å	all	Sc 9
	5349.3 Å 5349.7 Å	all	Sc 10
	5356.1 Å	all	Sc 11
	5375.4 Å	all	Sc 12
	5392.1 Å	all	Sc 13
	5446.3 Å 5451.5 Å	all	Sc 14
	5482.0 Å 5484.7 Å	all	Sc 15
	5514.2 Å 5515.0 Å	all	Sc 16
	5671.8 Å	all	Sc 17

Table 4.1 Continued

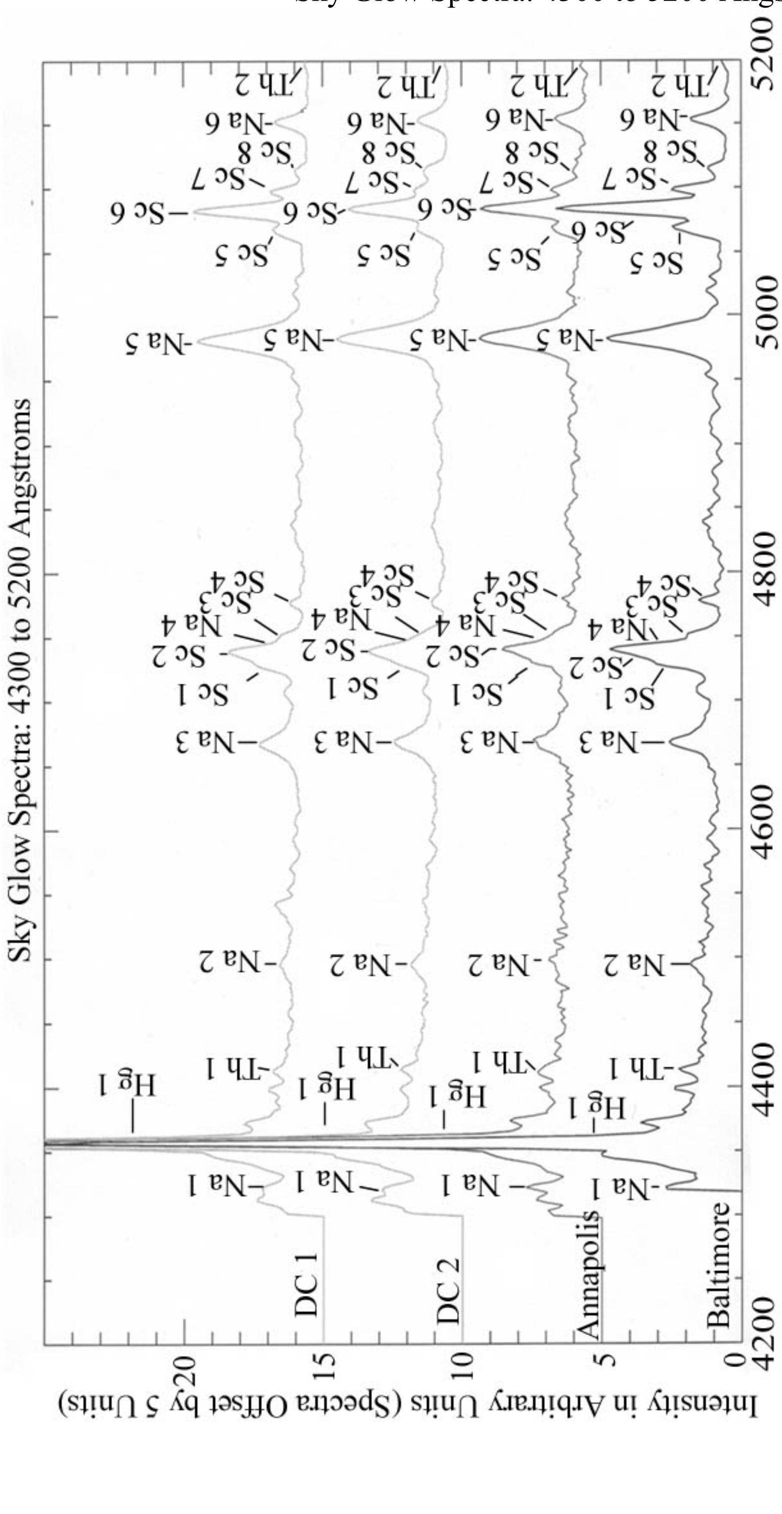
Spectral Features Identified in Sky Glow Spectra

Element Responsible	Feature		
	Wavelength(s)	Spectra Containing	Key to Features in Figures
Scandium	5686.9 Å	all	Sc 18
	5700.2 Å	all	Sc 19
	5708.6 Å	all	Sc 20
	5711.8 Å 5717.3 Å 5724.1 Å	all	Sc 21
	6210.7 Å	all	Sc 22
	6259.0 Å	all	Sc 23
	6985.6 Å	Annapolis, Baltimore	Sc 24
	7127.2 Å 7127.8 Å	DC 1	Sc 25
	7428.9 Å	DC 1	n/a
	7453.1 Å	DC 1	n/a
MH Lamps	6193 Å	all	MH 1
	6240 Å	all	MH 2
	6413 Å	all	MH 3
	6457 Å	all	MH 4
	6591 Å	all	MH 5

This table catalogs the NIST published wavelength of every spectral feature identified in the sky glow spectra with the exception of the sodium D lines emission-absorption feature in HPS lamps. The five unknown MH features are identified only to a precision of 1 Å because this was the approximate accuracy of the wavelength data. Some features included here did not resolve into multiple lines, but NIST and other sources reported multiple lines within the width of the observed feature and the presence of these lines became evident when a Gaussian line-fitting procedure was used to fit lines to the features. In these cases, the feature is listed as a single entity but the wavelength of each line is given in the "Wavelength(s)" column. Several features are known to be part of the spectra of some metal halide lamps but could not be attributed to any specific element; for them the element responsible is listed as "MH lamps" The "Key to Features in Figures" column gives the labels used to identify the spectral features in figures 4.1 through 4.3. Some lines lie outside the range in which it was possible to intensity-calibrate the detector and thus are not shown in these figures, which are intensity-calibrated spectra. For these features, n/a is listed instead of a label. While most features were found in all spectra, some are only present in some spectra. In the "Spectra Containing" column, the spectra that contain a particular feature are identified. If a feature is in all spectra (DC 1, DC 2, Annapolis, and Baltimore), the word "all" is written, instead.

Figure 4.1

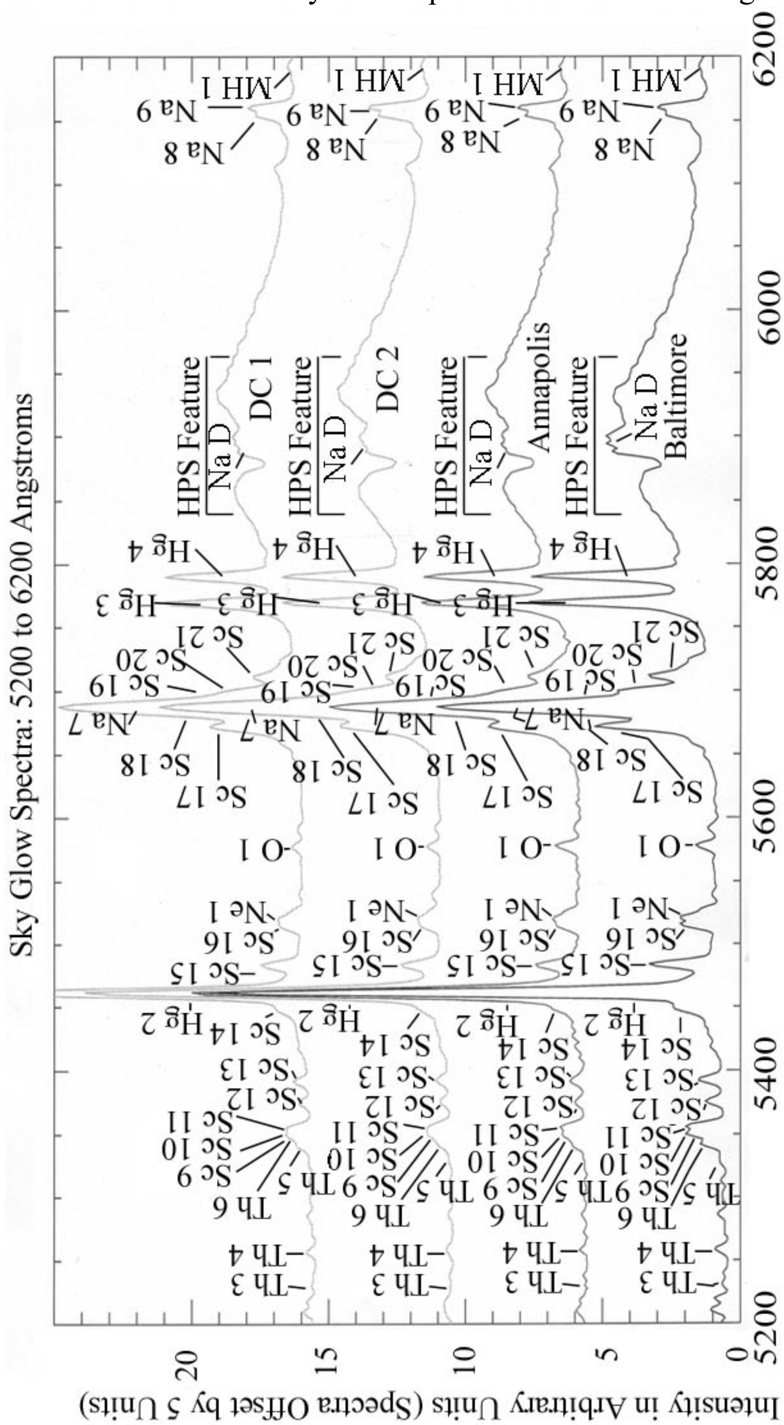
Sky Glow Spectra: 4300 to 5200 Angstroms



This figure shows four sky glow spectra over the range 4300 to 5200 Angstroms. They were collected as 10-minute exposures taken with a CCD and spectrograph attached to a 36" telescope at the Goddard Geophysical and Astronomical Observatory. The spectra have been corrected to account for the wavelength-sensitivity profile of the instrument. However, the continuum rise below 4600 Angstroms may be due to problems with this correction or to MH lamps. Identified spectral features are labeled by the element that produces them and keyed to Table 4.1, where the wavelength or wavelengths of the features can be found. Spectra are offset by five units and have been multiplied by correction factors to have the same total flux. Some features have been allowed to run off the top of the graph.

Figure 4.2

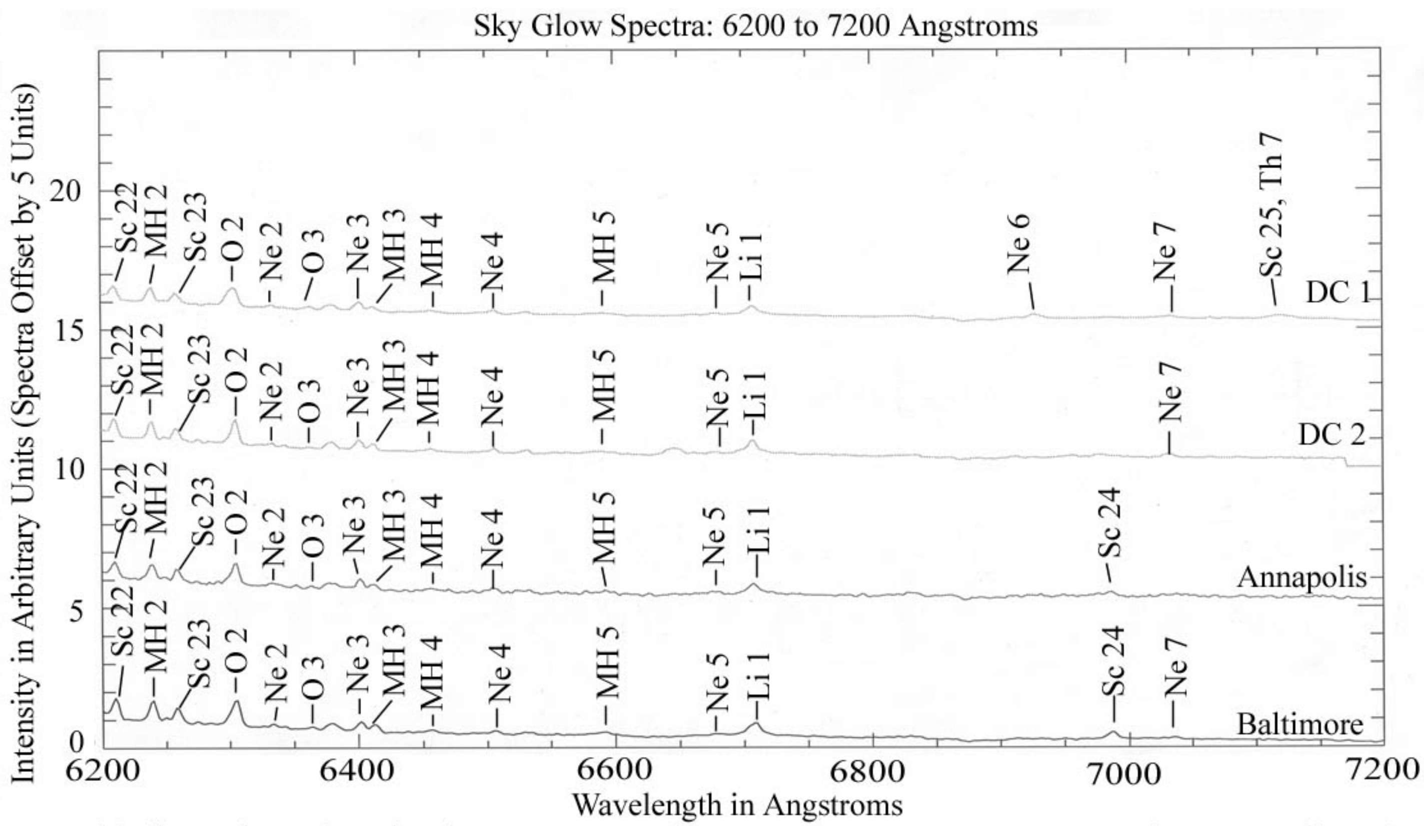
Sky Glow Spectra: 5200 to 6200 Angstroms



This figure shows four sky glow spectra over the range 5200 to 6200 Angstroms. They were collected as 10-minute exposures taken with a CCD and spectrograph attached to a 36" telescope at the Goddard Geophysical and Astronomical Observatory. The spectra have been corrected to account for the wavelength-sensitivity profile of the instrument. Identified spectral features are labeled by the element that produces them and keyed to Table 4.1, where the wavelength or wavelengths of the features can be found. Spectra are offset by five units and have been multiplied by correction factors to have the same total flux. Some features have been allowed to run off the top of the graph.

Figure 4.3

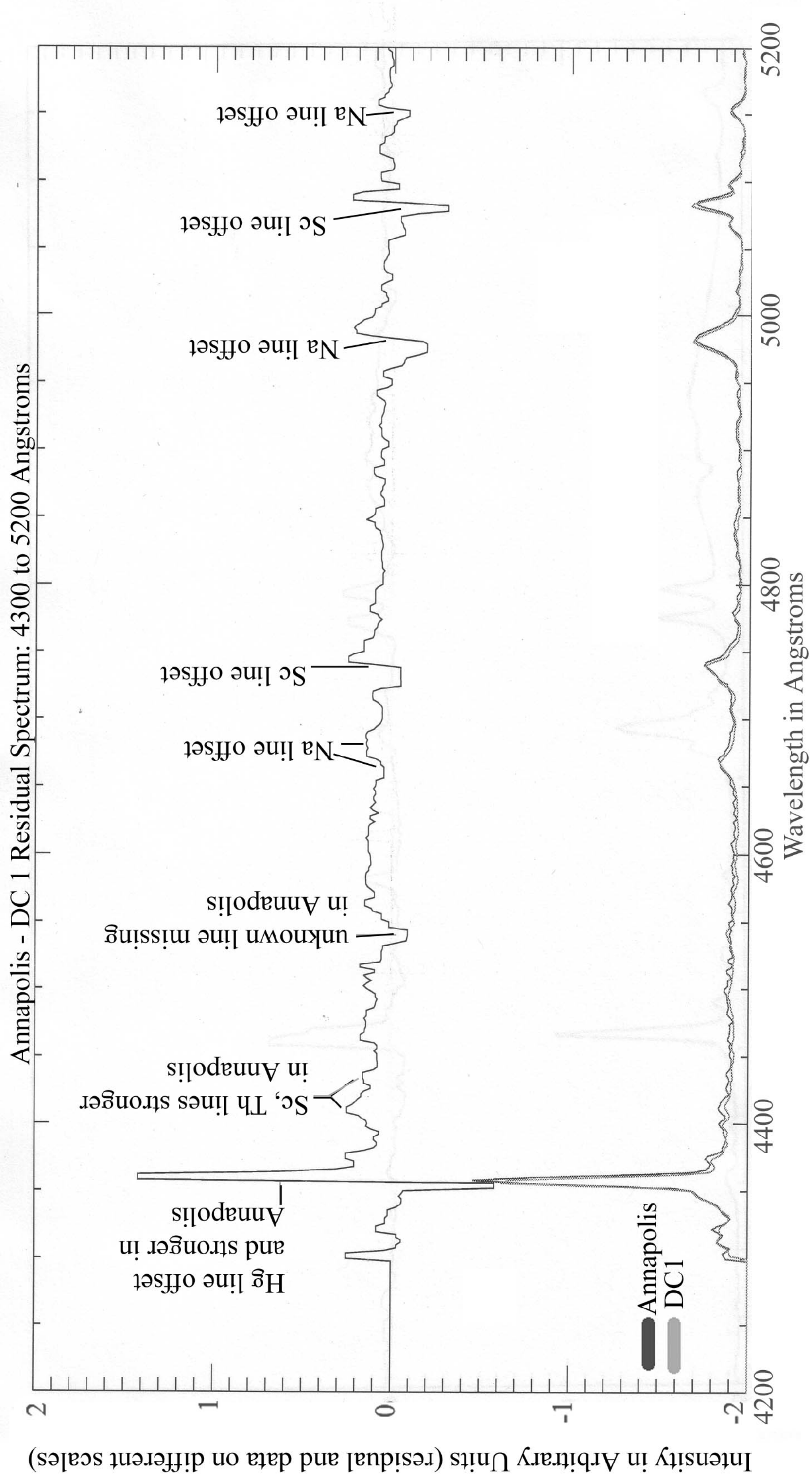
Sky Glow Spectra: 6200 to 7200 Angstroms



This figure shows four sky glow spectra over the range 6200 to 7200 Angstroms. They were collected as 10-minute exposures taken with a CCD and spectrograph attached to a 36" telescope at the Goddard Geophysical and Astronomical Observatory. The spectra have been corrected to account for the wavelength-sensitivity profile of the instrument. Identified spectral features are labeled by the element that produces them and keyed to Table 4.1, where the wavelength or wavelengths of the features can be found. Spectra are offset by five units and have been multiplied by correction factors to have the same total flux.

Figure 4.4

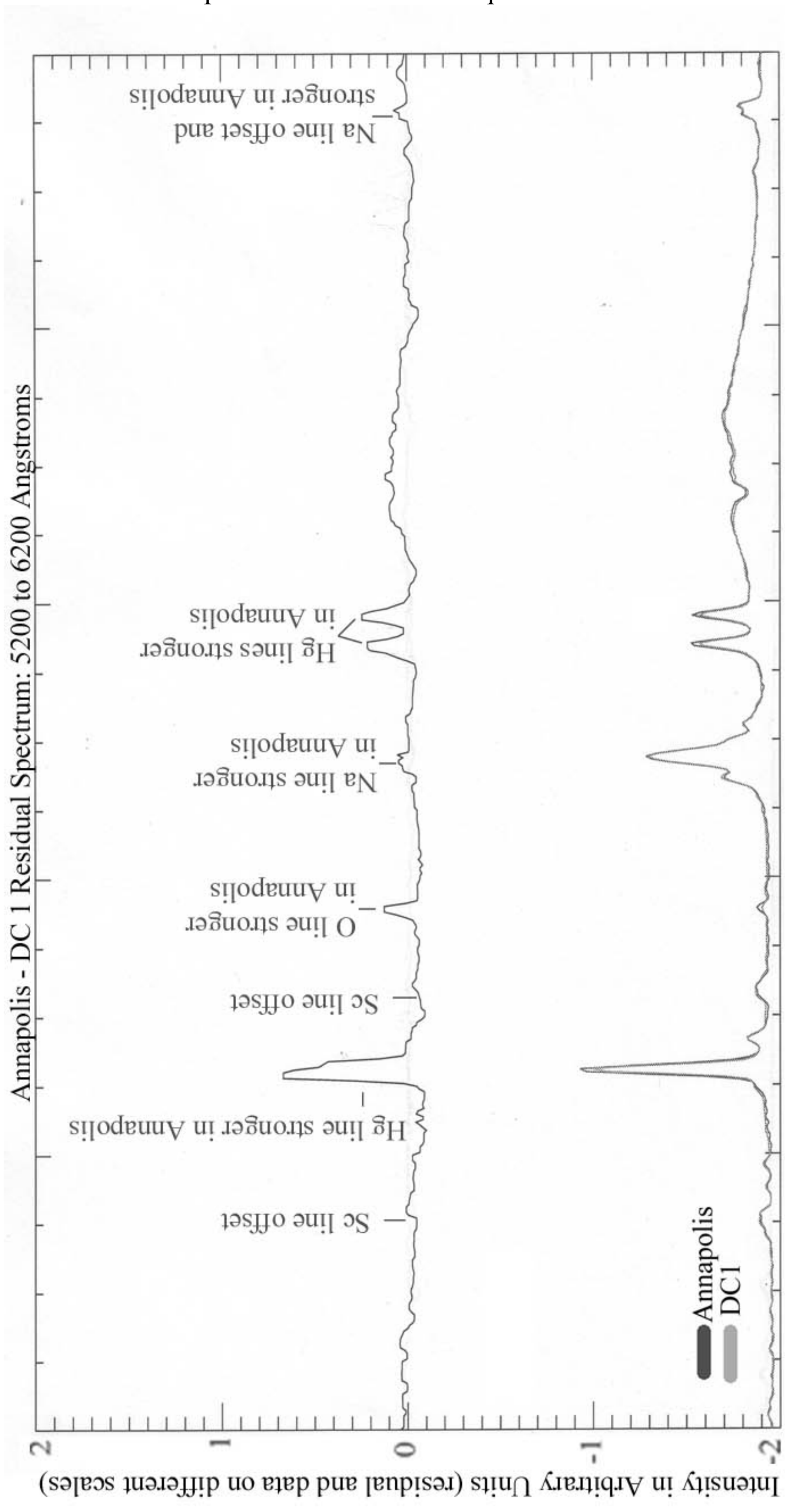
Annapolis – DC 1 Residual Spectrum: 4300 to 5200 Angstroms



This residual spectrum was produced by subtracting the DC 1 spectrum from the Annapolis spectrum and median filtering the result with a window size of 5 pixels. Features in this residual that are primarily above or below the 0 line suggest that a line or is relatively more intense in one spectrum. Features that seem to be equally above and below the 0 line are generally the result of a line profile differing between the two spectra or a slight offset in the center of the feature. In the case of the Na and Sc lines here, it appears to be the result of line profile differences, which may suggest different brands of lights in the two cities.

Figure 4.5

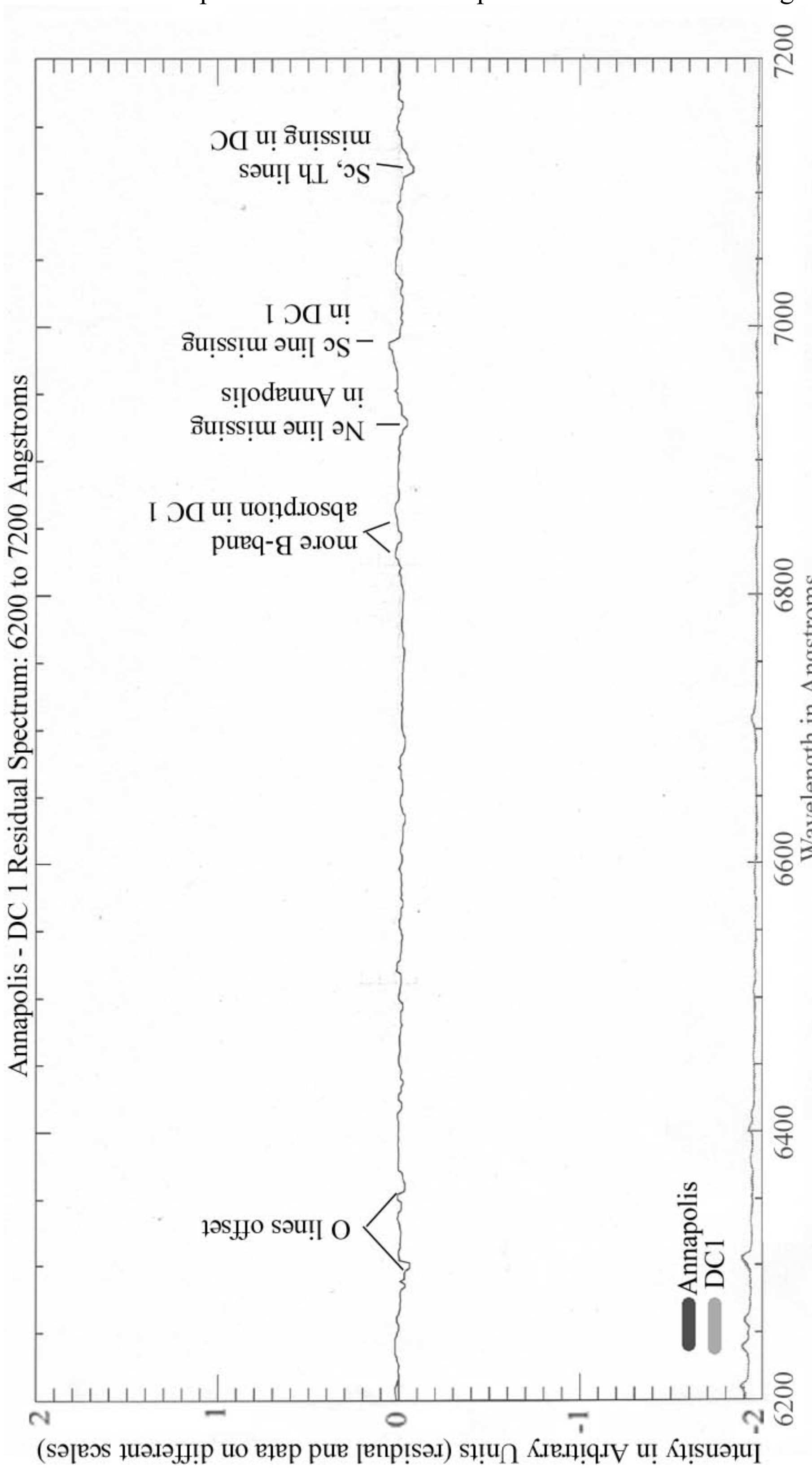
Annapolis – DC 1 Residual Spectrum: 5200 to 6200 Angstroms



This residual spectrum was produced by subtracting the DC 1 spectrum from the Annapolis spectrum and median filtering the result with a window size of 5 pixels. Features in this residual that are primarily above or below the 0 line suggest that a line or feature is relatively more intense in one spectrum. Features that seem to be equally above and below the 0 line are generally the result of a line profile differing between the two spectra or a slight offset in the center of the feature. In the case of the Na and Sc lines here, it appears to be the result of line profile differences, which may suggest different brands of lights in the two cities.

Figure 4.6

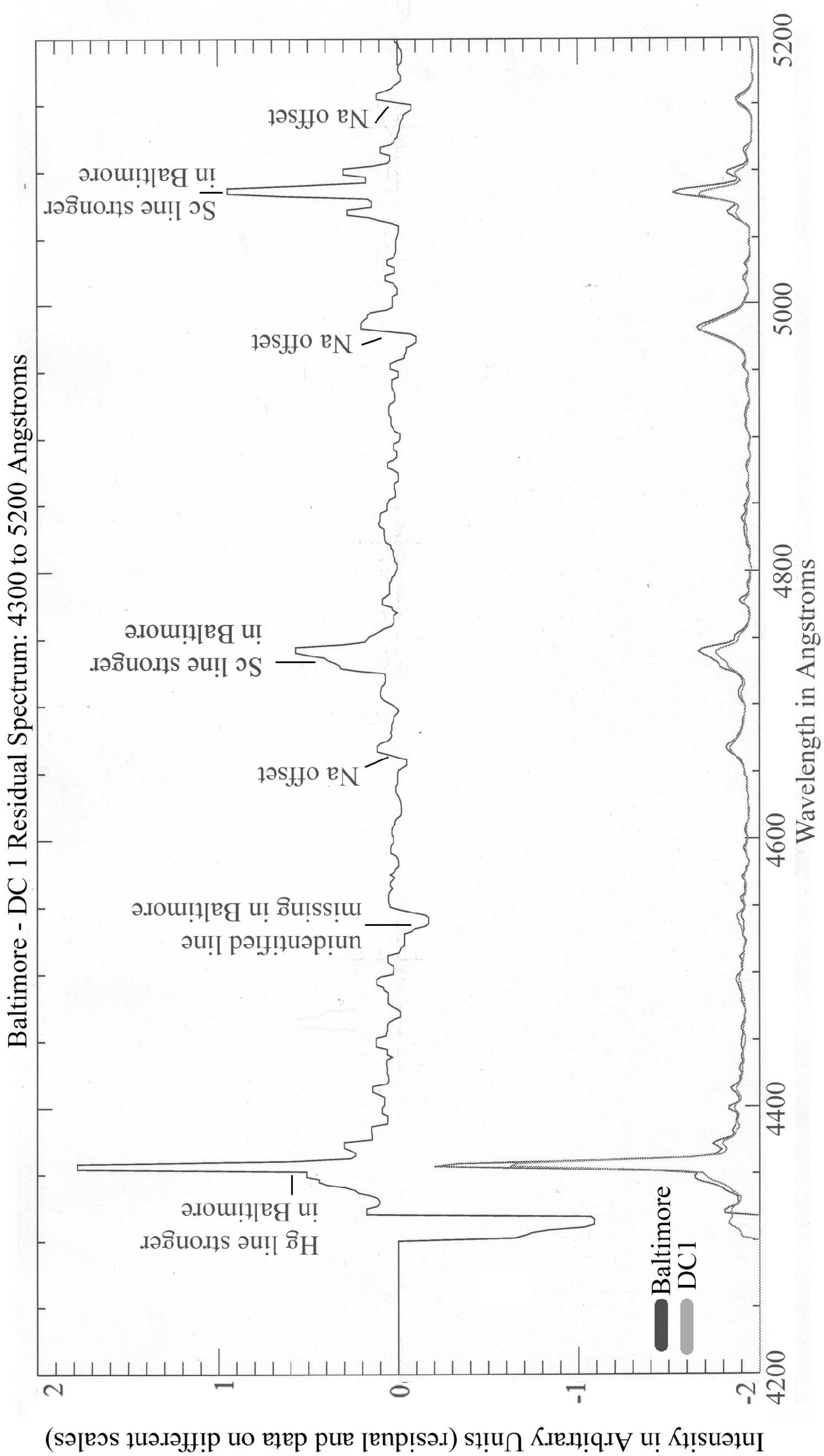
Annapolis – DC 1 Residual Spectrum: 6200 to 7200 Angstroms



This residual spectrum was produced by subtracting the DC 1 spectrum from the Annapolis spectrum and median filtering the result with a window size of 5 pixels. Features in this residual that are primarily above or below the 0 line suggest that a line or feature is relatively more intense in one spectrum. Features that seem to be equally above and below the 0 line are generally the result of a line profile differing between the two spectra or a slight offset in the center of the feature. In the case of the Sc lines here, it appears to be the result of line profile differences, which may suggest different brands of lights in the two cities.

Figure 4.7

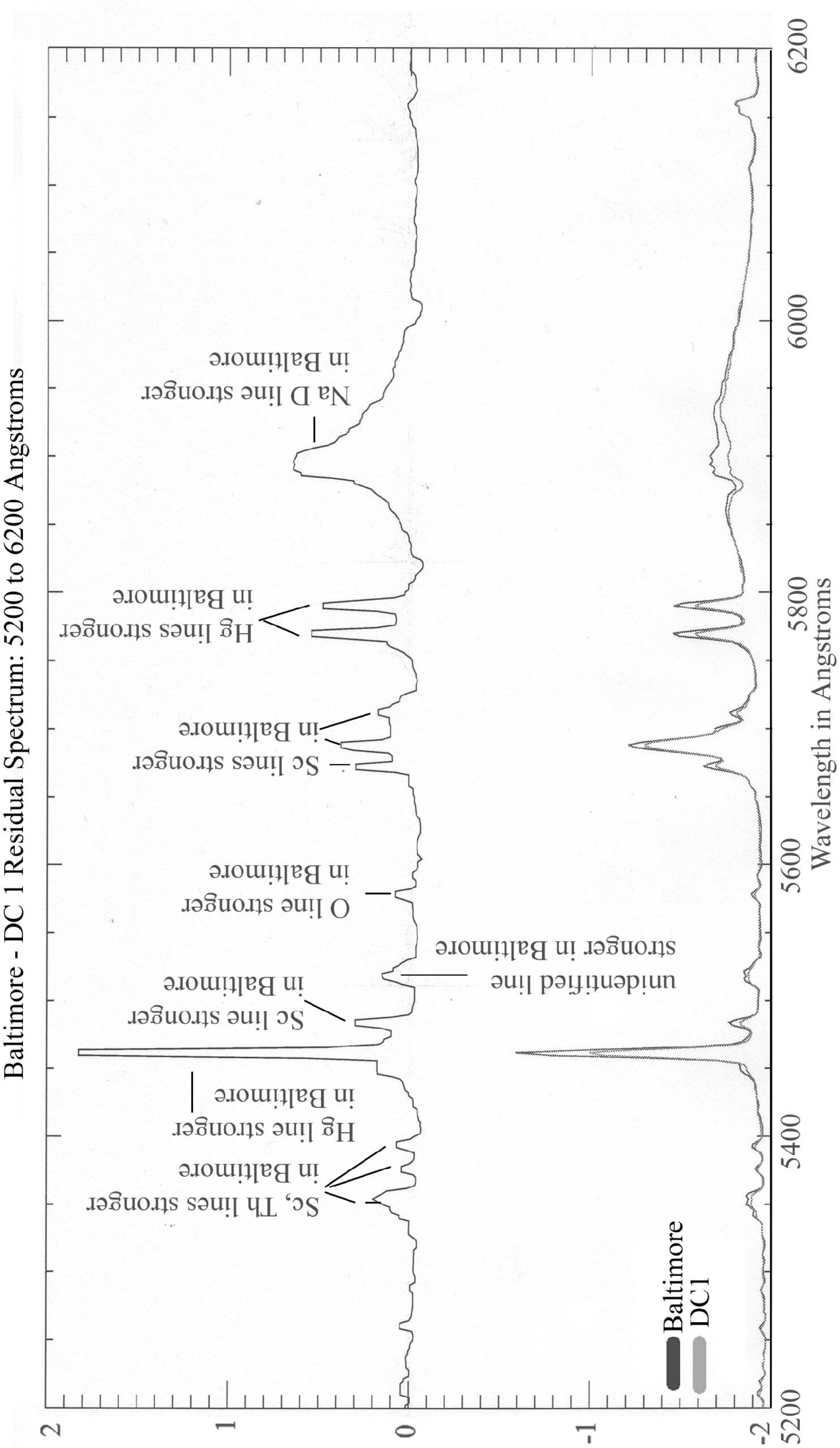
Baltimore – DC 1 Residual Spectrum: 4300 to 5200 Angstroms



This residual spectrum was produced by subtracting the DC 1 spectrum from the Baltimore spectrum and median filtering the result with a window size of 5 pixels. Features in this residual that are primarily above or below the 0 line suggest that a feature is relatively more intense in one spectrum. Features that seem to be equally above and below the 0 line are generally the result of a line profile differing between the two spectra or a slight offset in the center of the feature. In the case of the Na lines here, it appears to be the result of different types of Na lights in Baltimore. This is also suggested by the strong Na D line.

Figure 4.8

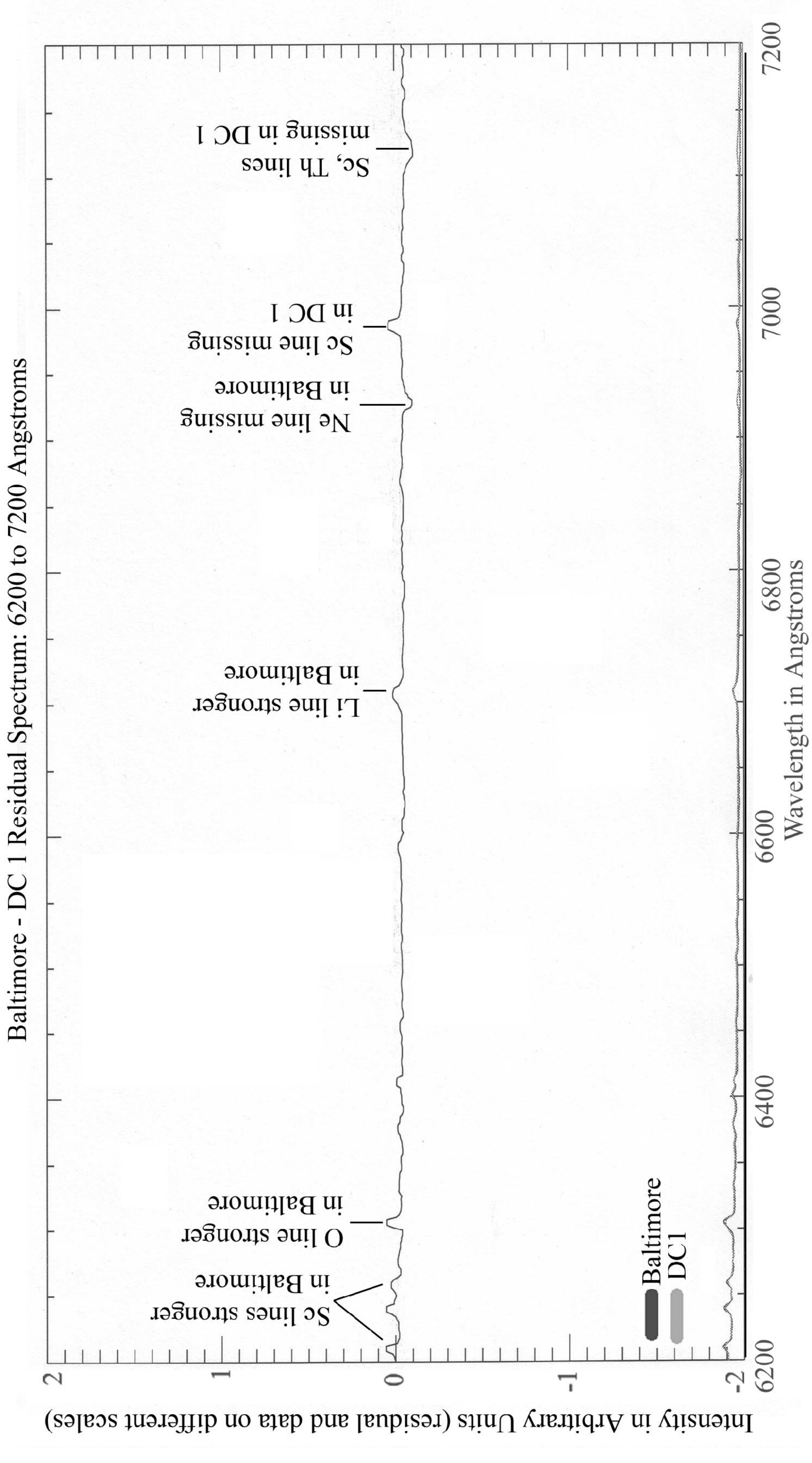
Baltimore – DC 1 Residual Spectrum: 5200 to 6200 Angstroms



This residual spectrum was produced by subtracting the DC 1 spectrum from the Baltimore spectrum and median filtering the result with a window size of 5 pixels. Features in this residual that are primarily above or below the 0 line suggest that a line or feature is relatively more intense in one spectrum. Features that seem to be equally above and below the 0 line are generally the result of a line profile differing between the two spectra or a slight offset in the center of the feature. In the case of the Na lines here, it appears to be the result of different types of Na lights in Baltimore. This is also suggested by the strong Na D line.

Figure 4.9

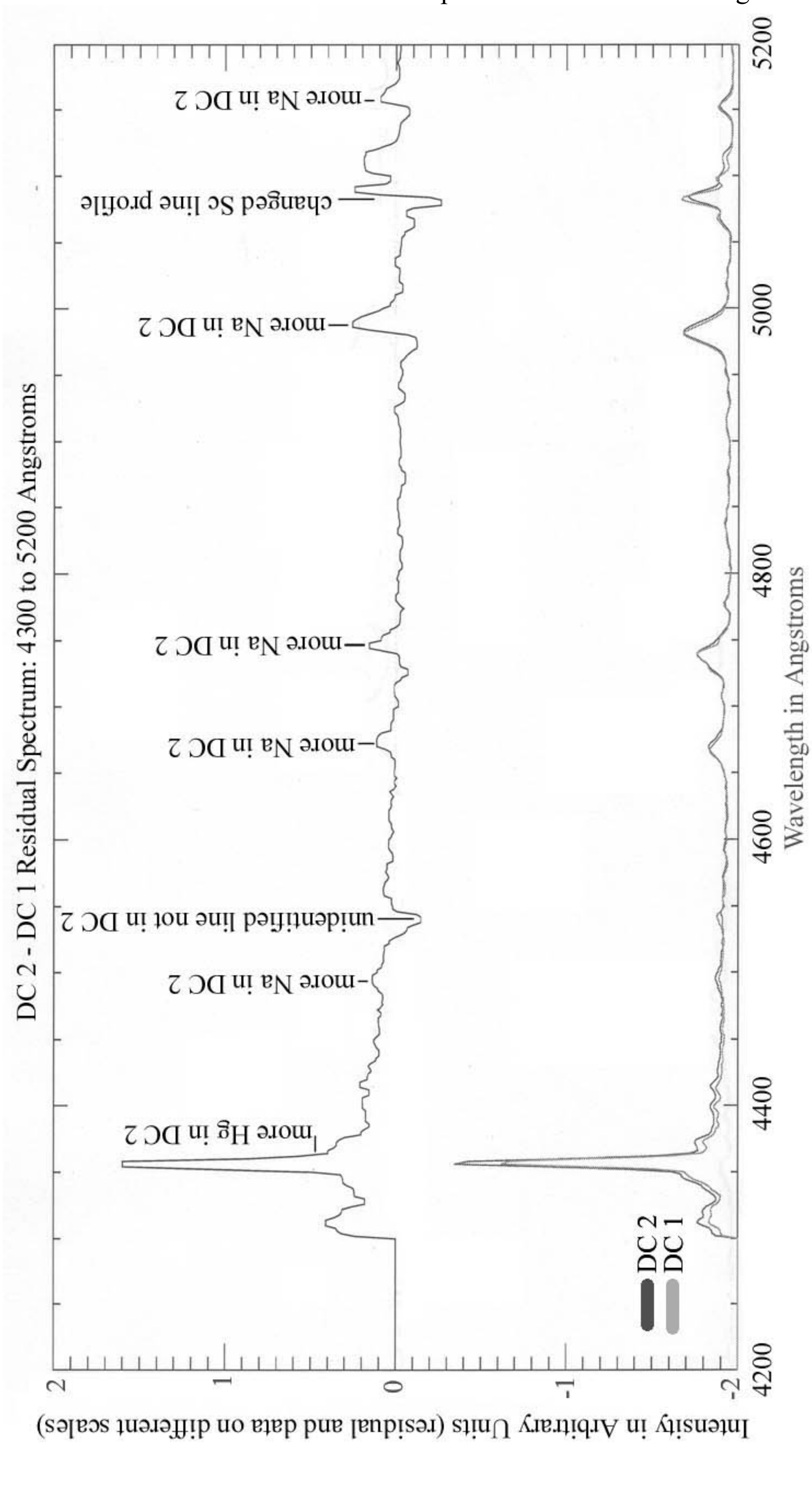
Baltimore – DC 1 Residual Spectrum: 6200 to 7200 Angstroms



This residual spectrum was produced by subtracting the DC 1 spectrum from the Baltimore spectrum and median filtering the result with a window size of 5 pixels. Features in this residual that are primarily above or below the 0 line suggest that a line or feature is relatively more intense in one spectrum. Features that seem to be equally above and below the 0 line are generally the result of a line profile differing between the two spectra or a slight offset in the center of the feature. In the case of the Na lines here, it appears to be the result of different types of Na lights in Baltimore. This is also suggested by the strong Na D line.

Figure 4.10

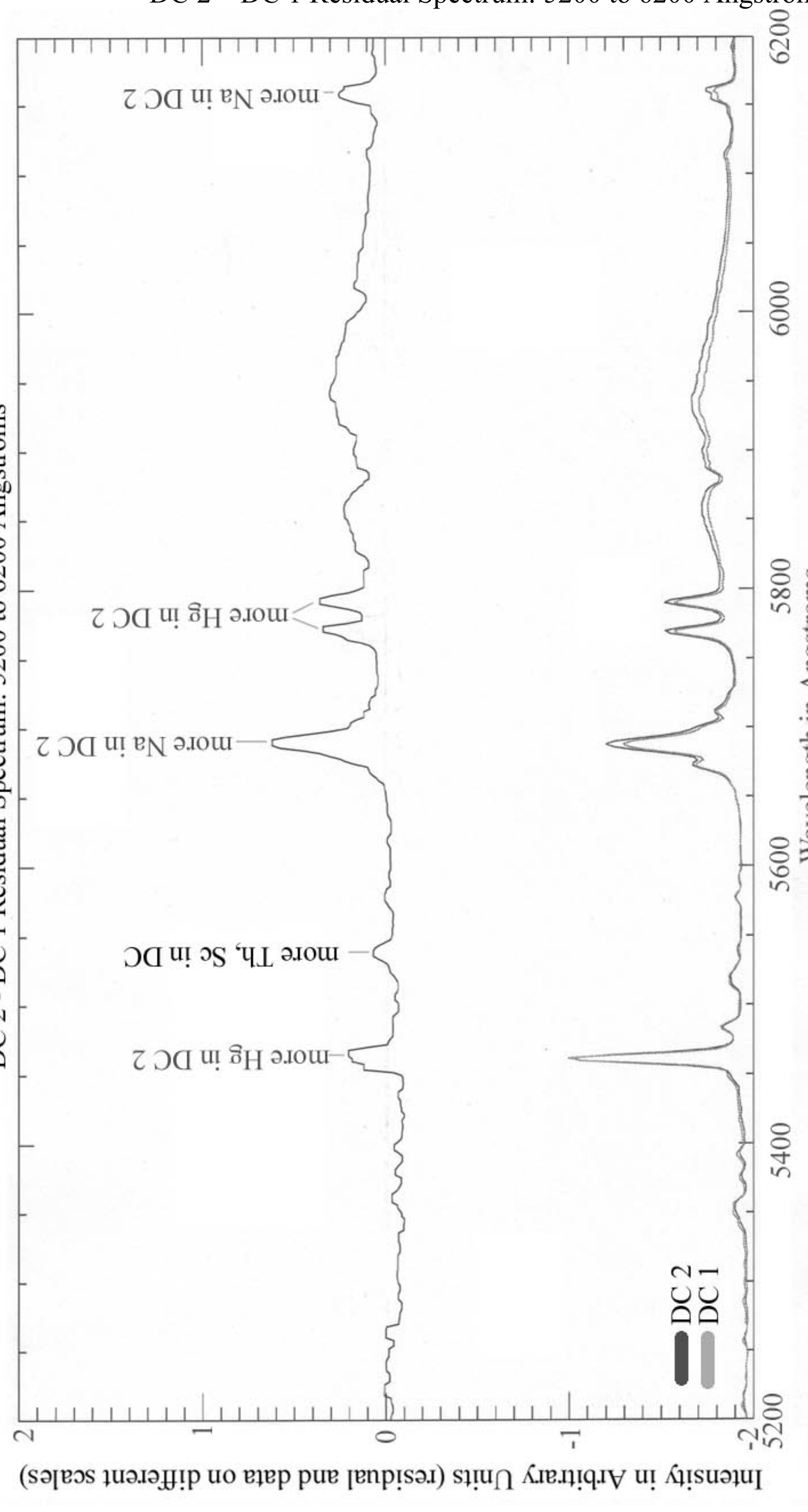
DC 2 – DC 1 Residual Spectrum: 4300 to 5200 Angstroms



This residual spectrum was produced by subtracting the DC 1 spectrum from the DC 2 spectrum and median filtering the result with a window size of 5 pixels. Features in this residual that are primarily above or below the 0 line suggest that a line or feature is relatively more intense in one spectrum. Features that seem to be equally above and below the 0 line are generally result of a line profile differing between the two spectra or a slight offset in the center of the feature. Both of these latter effects may be promoted in this case by the unusually great offset required to line up the DC 1 and DC 2 spectra.

Figure 4.11

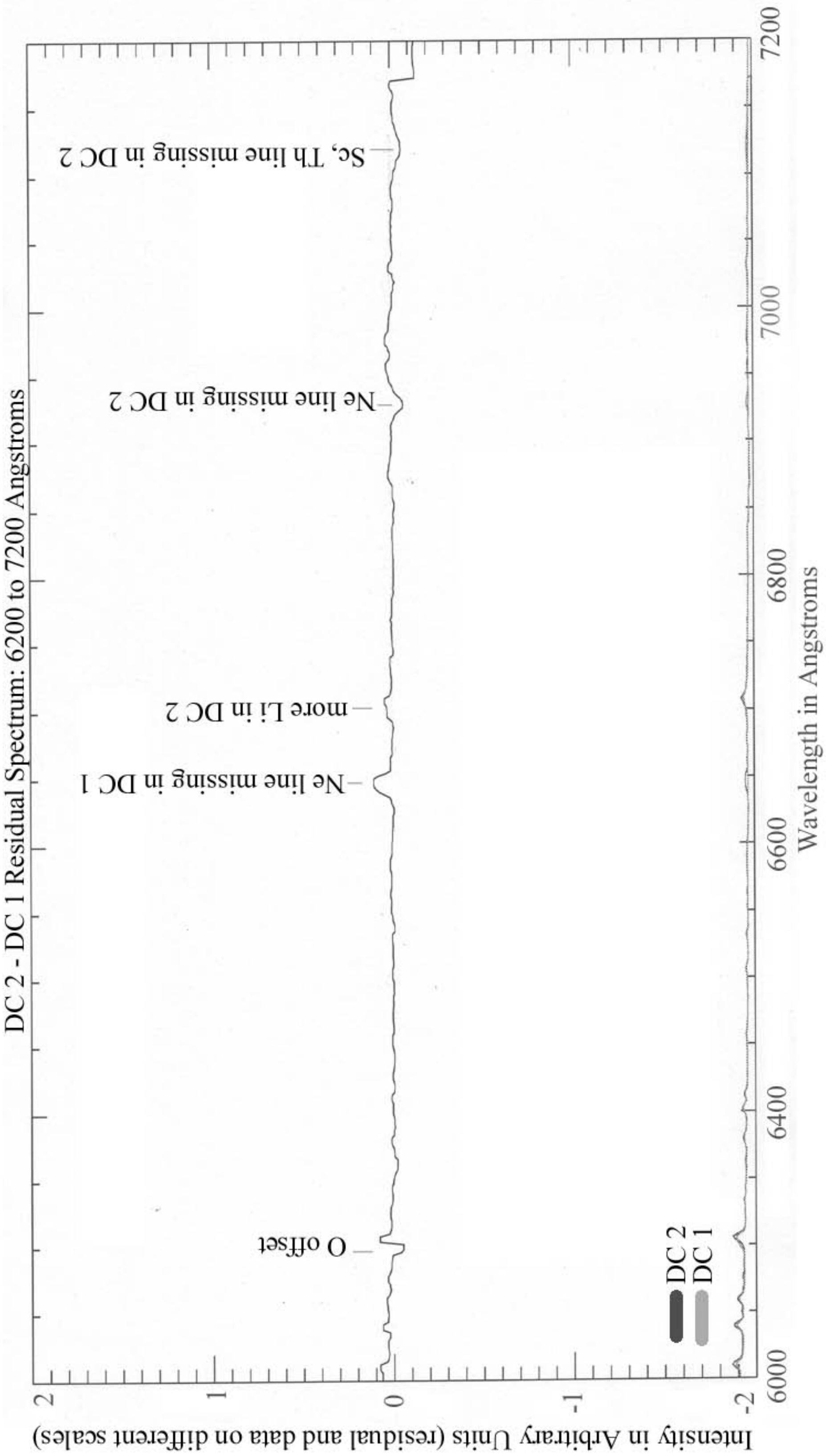
DC 2 – DC 1 Residual Spectrum: 5200 to 6200 Angstroms



This residual spectrum was produced by subtracting the DC 1 spectrum from the DC 2 spectrum and median filtering the result with a window size of 5 pixels. Features in this residual that are primarily above or below the 0 line suggest that a line or feature is relatively more intense in one spectrum. Features that seem to be equally above and below the 0 line are generally the result of a line profile differing between the two spectra or a slight offset in the center of the feature. Both of these latter effects may be promoted in this case by the unusually great offset required to line up the DC 1 and DC 2 spectra.

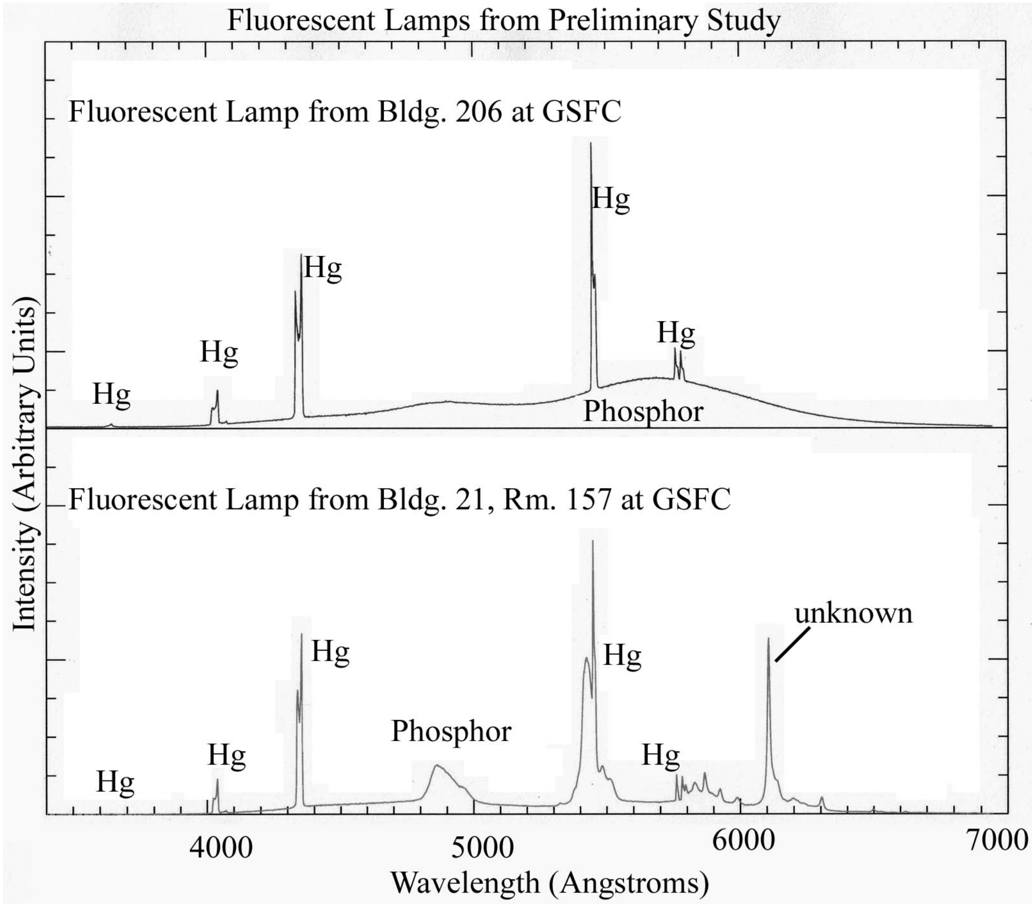
Figure 4.12

DC 2 – DC 1 Residual Spectrum: 6200 to 7200 Angstroms



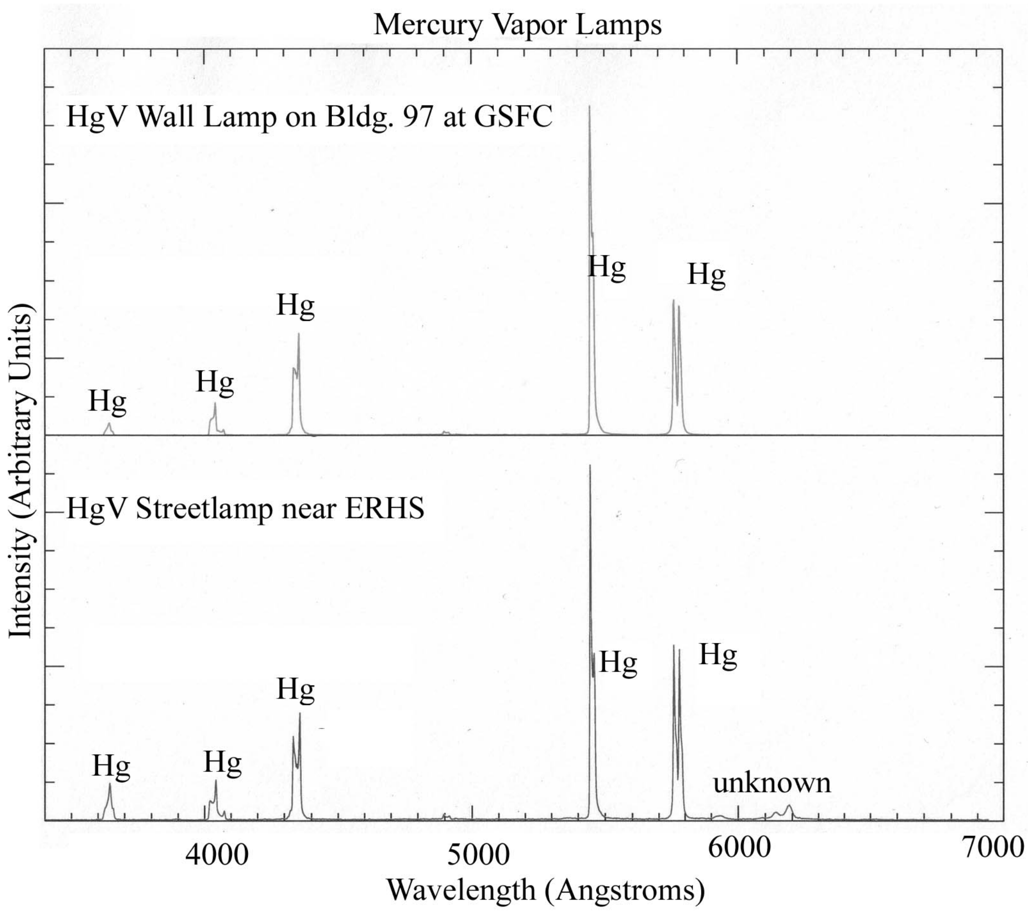
This residual spectrum was produced by subtracting the DC 1 spectrum from the DC 2 spectrum and median filtering the result with a window size of 5 pixels. Features in this residual that are primarily above or below the 0 line suggest that a line oı feature is relatively more intense in one spectrum. Features that seem to be equally above and below the 0 line are generally th result of a line profile differing between the two spectra or a slight offset in the center of the feature. Both of these latter effects may be promoted in this case by the unsusually great offset required to line up the DC 1 and DC 2 spectra.

Figure 4.13



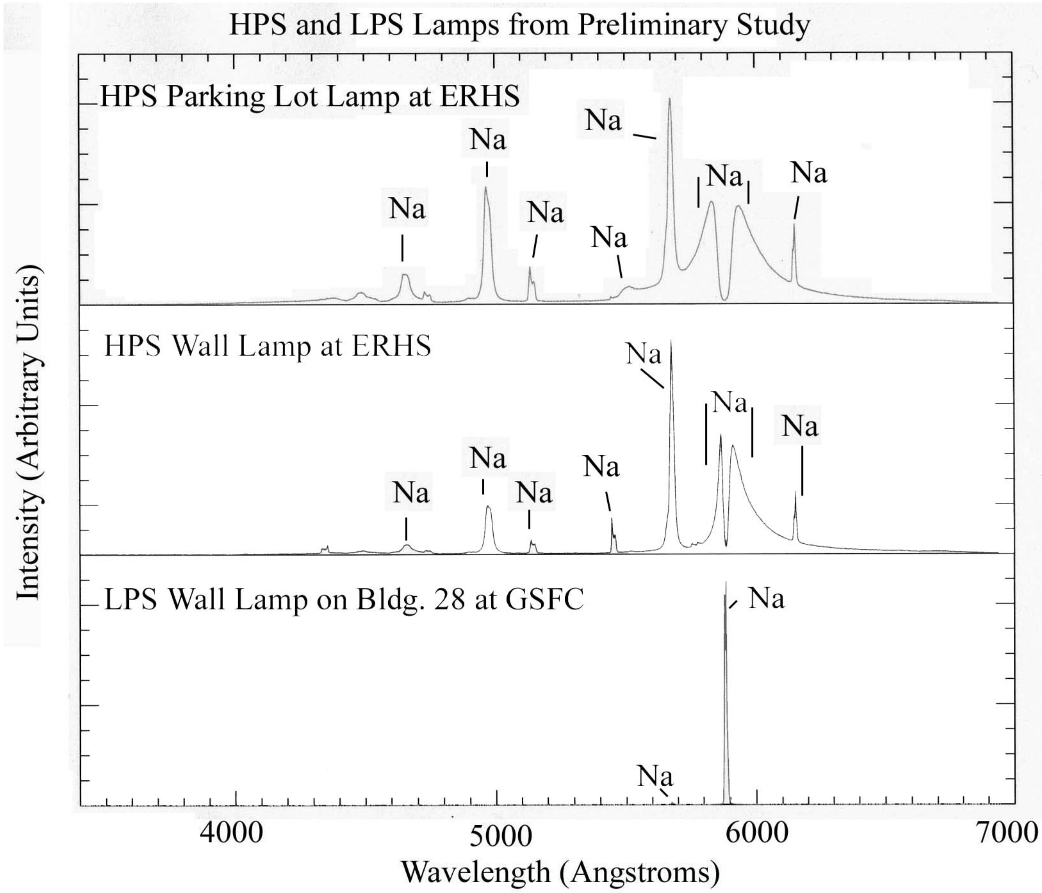
These are spectra of fluorescent lamps at the Goddard Space Flight Center (GSFC) during the preliminary study. They were taken with a portable spectrometer as part of the preliminary study. Several spectral features have been identified.

Figure 4.14



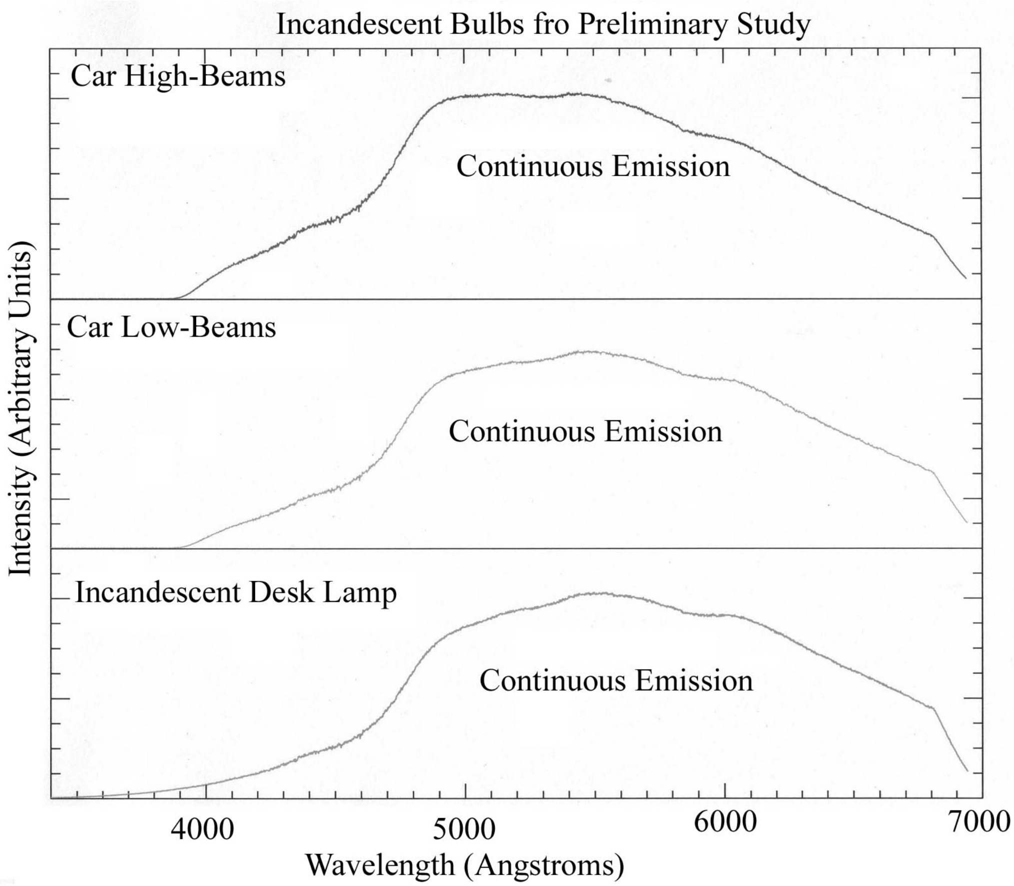
These are the spectra of two mercury vapor lamps at Eleanor Roosevelt High School (ERHS) and Goddard Space Flight Center (GSFC) taken during the preliminary study. Mercury features are marked in them.

Figure 4.15



These are the spectra of several HPS and LPS lamps near Eleanor Roosevelt High School and the Goddard Space Flight Center. They were taken with a portable spectrometer as part of the preliminary study. Several spectral features have been identified.

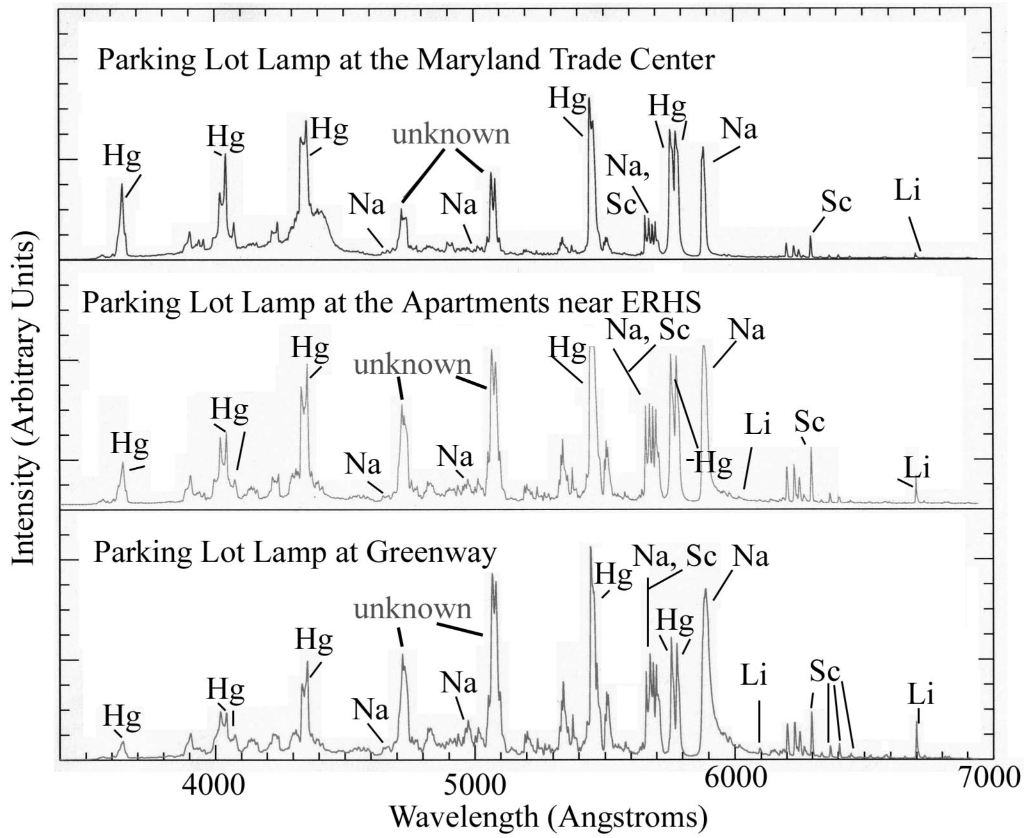
Figure 4.16



These are the spectra, taken during the preliminary study, of incandescent bulbs, both in car headlights and in a desk lamp. The entire spectrum consists of a continuous emission feature. Incandescent bulbs typically emit light characteristic of a 3000 K blackbody source and thus emit most of their radiation in the near-infrared. The dropoff in the red here is due to decreasing detector sensitivity.

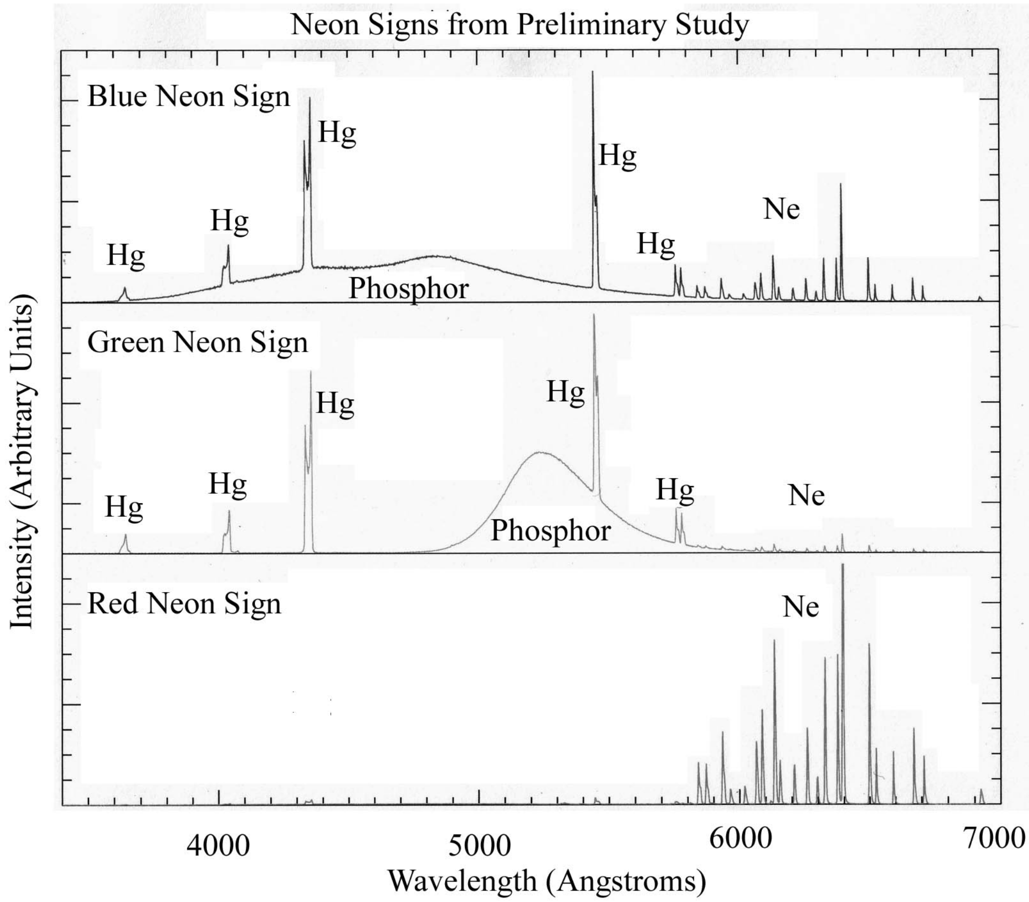
Figure 4.17

Metal Halide Lamps from Preliminary Study



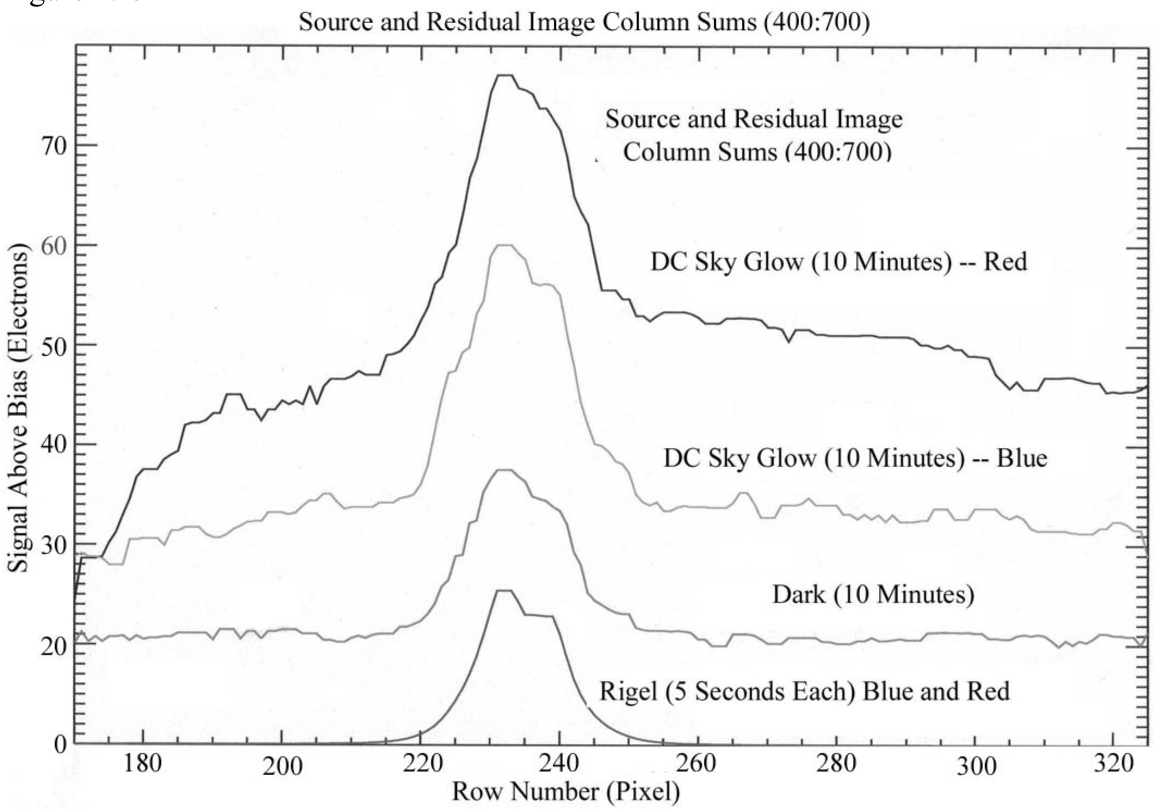
These are the spectra of several metal halide lamps at the apartment complex near Eleanor Roosevelt High School (ERHS), the Greenway shopping center, and the nearby Maryland Trade Center office building. They were taken with a portable spectrometer as part of the preliminary study. Several spectral features have been identified.

Figure 4.18



These are the spectra of several neon signs the Goddard Space Flight Center. They were taken with a portable spectrometer as part of the preliminary study. Several spectral features have been identified.

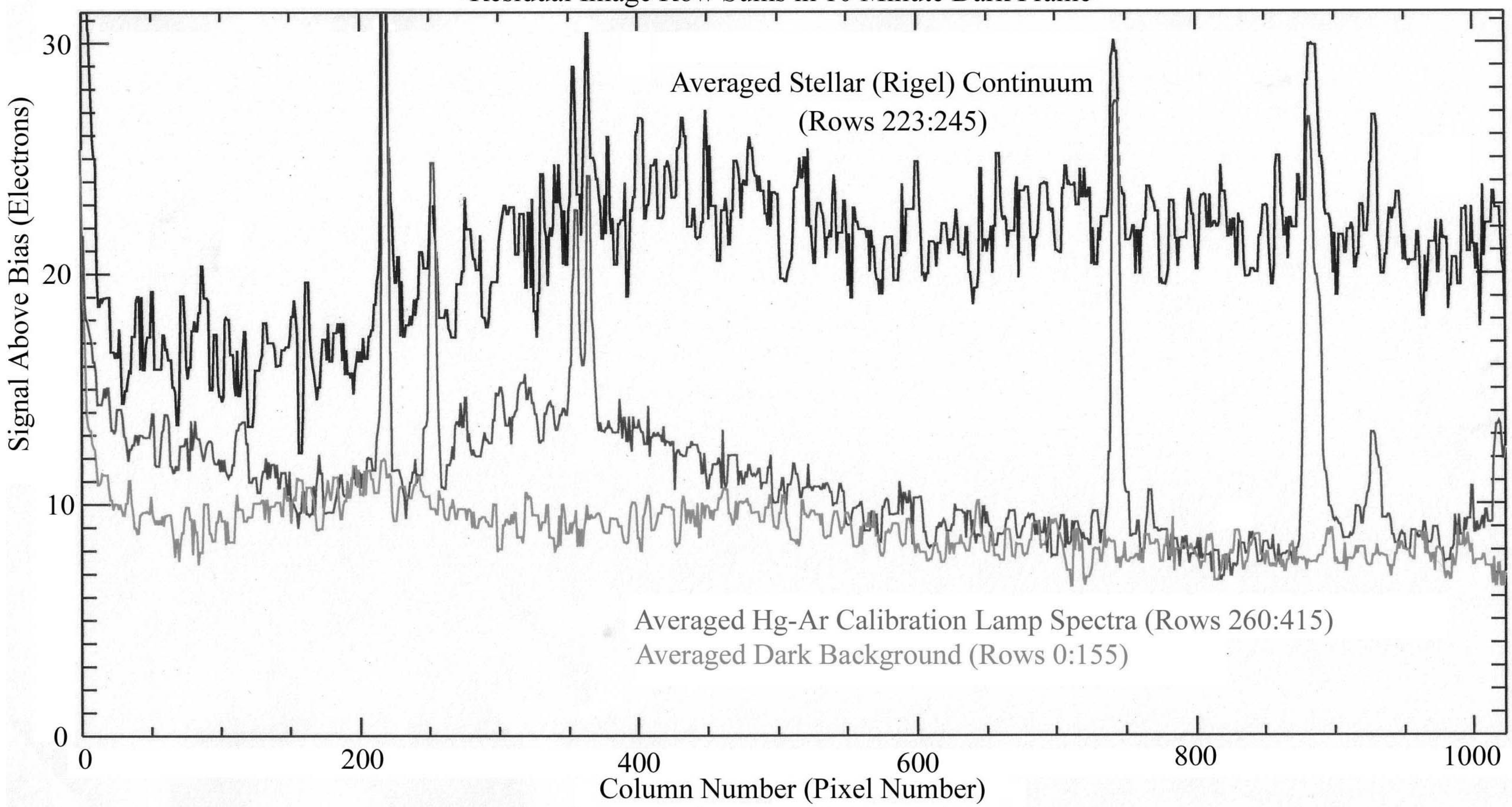
Figure 4.19



This is a plot of the spectral profile of several spectra. That is, it shows the CCD detector summed along the columns, perpendicular to the spectral dispersion. The bottom profile is that of Rigel spectra. The other profiles are of spectra that were taken afterward--the bump in them is an afterimage of the Rigel spectra and not an actual component of the DC sky glow spectra and the dark current of the CCD. The times given are exposure times.

Figure 4.20

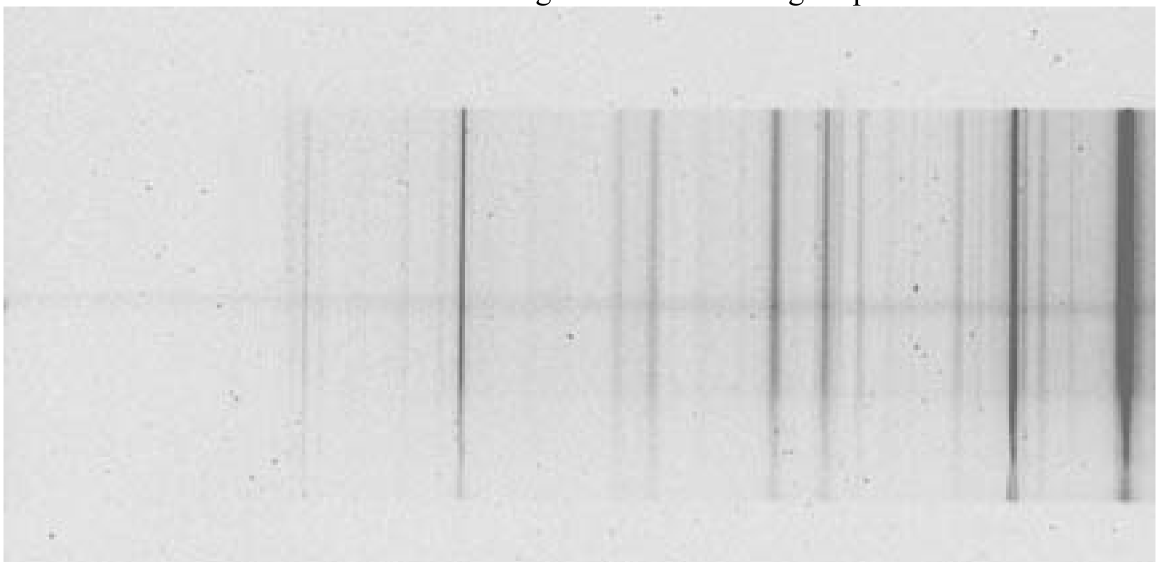
Residual Image Row Sums in 10 Minute Dark Frame



This is a plot of the average signal above bias (in terms of number of photons detected) in three regions of the CCD detector. This image was taken as a dark frame (with the shutter closed) and should have no signal except for dark current. This is true of rows 0:155 of the detector, which are never exposed to light. However, rows 260:415, which are exposed to light when calibration lamp spectra are taken, show a residual calibration lamp spectrum and rows 223:245, which are exposed to light whenever spectra are taken show both a residual calibration lamp spectrum and a residual Rigel spectrum. Sky glow spectra are not bright enough to leave visible residuals, though.

Figure 4.21

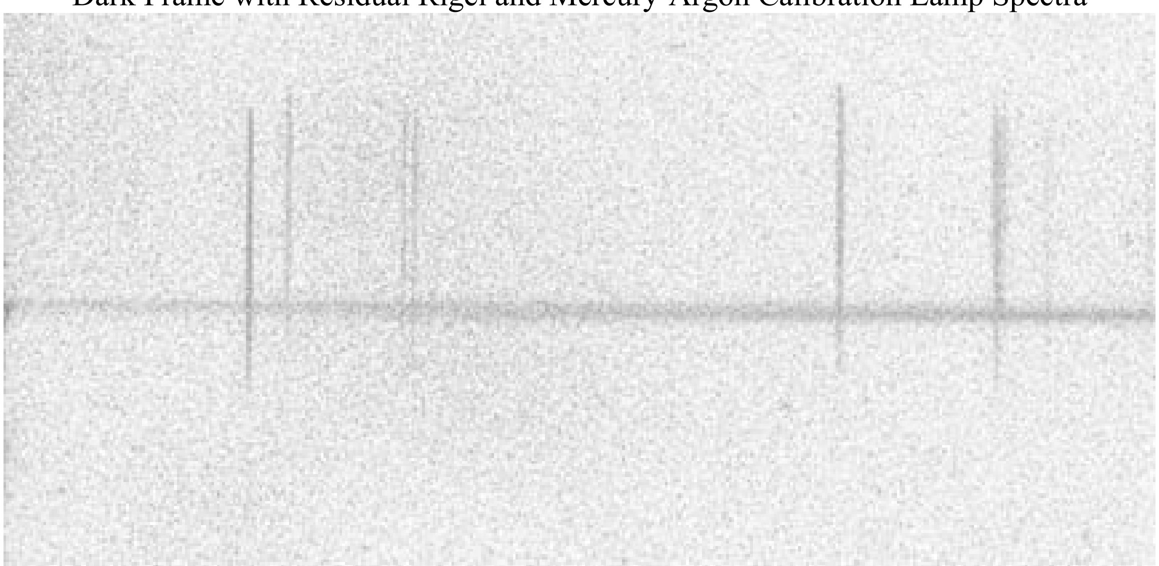
Blue DC 2 Raw CCD Image with Residual Rigel Spectrum



This figure is a negative of the raw CCD image of the blue DC 2 spectrum. It contains a burned-in Rigel spectrum (the horizontal line approximately halfway up from the bottom that runs the length of the frame). It also shows the cosmic ray hits (dark splotches) which were removed using the IDL procedure sky_reduce (see Appendix 1), which was written for this project. Note that printing may introduce spurious horizontal lines.

Figure 4.22

Dark Frame with Residual Rigel and Mercury-Argon Calibration Lamp Spectra



This figure is a negative of a raw CCD image that should be a dark frame. However, it contains a burned-in Rigel spectrum (the horizontal line that runs the length of the frame) and several burned in mercury-argon lamp spectra (the vertical lines about half of the height of the frame). Because the spectra were taken with the diffraction grating in different positions, the spectra do not line up along one wavelength scale. Figure 4.20 graphs of the signal against the length of the CCD along different rows in this frame.

Chapter Five

Conclusions

Summary

Light pollution is a serious problem in the world today: when one wastes light, one wastes electricity, interferes with astronomy, and can have negative impacts on plants and animals. However, it is not only the amount of light wasted that matters, but the type of light. Different types of light sources emit light with different spectra: LPS lamps are monochromatic; neon signs and HPS, MH, and HgV lamps have emission line spectra; and incandescent / halogen lamps emit continuous spectra. Some of these light sources are a bigger problem for astronomers than others, since some of them are harder to filter out of astronomical observations than others. Also, since different colors of light tend to have different impacts on organisms, some light sources may have more negative impacts on the environment than others. In addition, since some types of lamps are more energy efficient, light pollution produced by them wastes less electricity than light pollution produced by lamps that are more inefficient.

In any large urban area, many types of lighting will be present. This means that the properties of the light pollution in an urban area will be the properties of a combination of contributions from many types of lights. To determine how much any specific type of lighting contributes to the sky glow and to determine the overall properties of the sky glow in an area, it is necessary to take spectra of the sky glow. In this study, the spectra of the sky glow over the cities of Washington, DC; Baltimore, MD, Laurel, MD, and Columbia, MD (taken as a group under the name Baltimore); and Annapolis, MD and Bowie, MD (taken as a group under the name Annapolis) were compared. The spectra of DC in the early evening and around midnight were compared, as well. Spectra were also collected of lights sources in the field so that their spectra could be compared to those of the sky glow. Wavelength-dispersion fits were found for the spectra and Gaussian curve-fitting techniques were used to determine the makeup of blended emission-line features. A NIST database and a paper on the Mount Hamilton sky glow (Slanger, Cosby, Osterbrock, Stone, & Misch, 2003) were used to identify as many of the lines as possible and the field and sky spectra were then cross-calibrated so that the field spectra could be used to help identify the sources of other lines in the sky spectra. Wavelength-sensitivity fits were found for the detectors so that it was possible to produce spectra with the same intensity scale throughout.

Conclusion and Discussion

The hypothesis that HPS and HgV, and MH lights would be the dominant sources of light pollution in all cities at all times is supported. The dominance of the HPS emission-absorption feature in the red part of the spectrum and of mercury lines above sodium, neon, scandium, and thorium lines supports the hypothesis that HPS and HgV lights are dominant since the distorted sodium D lines are found only in HPS spectra and the mercury lines would be more similar in intensity to other lines if they had a major source other than HgV lamps. The presence of many scandium and thorium lines, of rather intense scandium lines, and of an MH-produced continuum in the blue end of the spectra suggests that MH lamps are more important as sources light pollution than neon signs, fluorescent lamps, or continuous emission lamps. It is unclear how they compare to HgV and HPS lamps, though. One cannot evaluate the intensity of LPS lamps to other lamps because the only significant LPS feature, the sodium D lines, is superimposed on the HPS emission-absorption feature.

The hypothesis that the fraction of the light produced by MH, HPS, LPS, and HgV lamps would increase over time is partly supported. The HPS and HgV lines in the normalized DC 2 spectra are clearly stronger than those in the normalized DC 1 spectra. However, the MH lines do not seem to change in intensity and the LPS sodium D lines do not seem to change in intensity, although this is hard to determine since they are superimposed over the HPS sodium D feature.

The hypothesis that Laurel and Columbia and Bowie and Annapolis would have a lower percentage of their light pollution supplied by neon (commercial) and MH/LPS/HPS/HgV (street lamp) lighting because these cities are not as commercially developed as Baltimore and Washington, DC is not supported. No comparison can be made between Baltimore and Laurel and Columbia because these cities were treated as though they were in the same direction during observation and individual spectra were not obtained for each city. As for the comparison between Washington and Bowie and Annapolis, the mercury lines seem stronger in Bowie and Annapolis and there seems to be some offset between the scandium, thorium, and sodium lines in the DC 1 spectra and the same lines in the Bowie and Annapolis spectra, suggesting that different brands of MH and HPS lights with different gas mixtures and pressures are used in these cities.

Although it is not relevant to a consideration of the hypotheses, it was noted that the LPS sodium D line is much stronger in the Baltimore spectra than it is in the other spectra. It was impossible, however, to determine whether Baltimore, Laurel, Columbia, or some combination of these was responsible for this. Also, one cannot be certain that this strengthened sodium D line is the result of an increased contribution to the sky glow from LPS lamps and not due to different gas pressures in HPS lamps in Baltimore, Laurel, and/or Columbia that caused a change in the shape of the HPS sodium D line feature.

Recommendations and Future Implications

One of the byproducts of this study has been a collection of knowledge about how not to study light pollution spectra. There are several things which one would want to do differently if one was to repeat this study. First of all, the resolution on the portable spectrometer used in the preliminary study was not as good as desired and, worse, the spectrometer produced many false doublets—it split single lines into doublets or triplets. This made it hard to identify a line both since one could not be sure if several associated features were one line or several and since one cannot perform a Gaussian line fit on a line that has been distorted to the point that it no longer resembles a Gaussian curve. Also, the CCD used with the spectrograph to collect the sky spectra was discovered to be defective during data analysis. Residual mercury-argon calibration lamp features, burnt in because the CCD chip did not properly reset itself between images, may have contaminated the sky glow data. Obviously, if this study was to be repeated, one would not want to use equipment with these flaws. Also, to simplify the process of determining wavelength-dispersion fits and of creating wavelength scales, it would be preferable to adjust the spectrograph so that the calibration lines are on the same pixels each time one switches between the blue and red grating settings. Also, it at all possible, it would be preferable to take spectra closer to the cities so that their individual contributions could be determined and it would not be necessary to combine several cities in one observation.

There are several topics related to this project which deserve further study. One issue is that the time-dependence of light pollution may be different on weekdays and on weekends and that it may be different in different cities.. Since the data in this study were collected on a Saturday, the contribution of car headlights to light pollution may have been more constant than it would have been on a weeknight when car headlights would be more significant during the evening rush hour and less significant once most commuters had arrived at their homes. It might also be worthwhile to conduct observations closer to the centers of cities of interest to avoid the problem (Cinzano & Stagni, 2000) that the sky glow produced by a light pollution source becomes redder as you move away from the source due to scattering of blue light in the atmosphere. This effect may have exaggerated the presence of sodium and neon features, which are farther to the red than mercury lines. Considering that the Maryland State Highway Administration and DC use HPS lighting almost exclusively for streetlights (Daniel Consultants, Inc., 2004), it might be worthwhile conducting a similar study in areas where different types of streetlights are more commonly used. If one wished to continue the study of light pollution in this area, it might also be worthwhile to take separate observations of Bowie and Annapolis and Laurel, Columbia, and Baltimore to determine whether these cities have similar light-pollution spectra or whether they produce different spectra that were superimposed because the spectra in this study were taken in directions that were contaminated with light pollution from multiple cities. It might also be worthwhile to conduct studies to determine which types of lighting are more or less harmful to plants and animals and whether the same lighting choices that minimize the impact of light pollution on astronomers and electricity consumption are the best choices from an environmental point of view. Light pollution has not been studied as thoroughly as other types of pollution produced by modern society and there are many aspects of it that deserve more research.

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Appendix 1

Procedure "sky_reduce"

This IDL procedure, sky_reduce, was written to process the sky glow spectra used in this project. It subtracts off the background from an image, rotates it to make the spectral lines perpendicular to the long side of the image, and uses several techniques to remove cosmic ray hits from the image. It finally collapses the image into a spectrum.

```
pro sky_reduce,qw,qwx,qwspec,resx,sdc1,sdc2,sdc3,row1,row2

;qw      input array
;qwx     output cosmic ray cleaned array
;qwspec          output cosmic ray clipped linear spectra
;resx    output residual array
;sdc1    # std deviations for 1st pass clipping
;sdc2    # std deviations for 2nd pass clipping
;sdc3    # std deviations for template clipping
;row1    # lower row definitely on slit
;row2    # upper row definitely on slit

;*****make window
window,20,xs=1024,ys=500
wset,20

;*****make qw0
bkgd = fltarr(2)
bkgd(0) = mean(qw(*,0:49))
bkgd(1) = mean(qw(*,449:499))
bk = min(bkgd)

qw0 = qw - bk
        print,'mean minimum background: '
        print,bk
        print,' '
```

```
;*****make qw1
qw1 = qw0
r10 = median(total(qw0(*,200:400),2)/201.0000 , 5)
r11 = max(r10)
        print,'qw0'
  tvscl,qw0<2*r11

x10 = where( qw0 gt 2*r11 )
if n_elements(x10) eq 1 then goto, scalar
qw1(x10) = ( qw0(x10+5120) + qw0(x10-5120) )/2
goto, pass1
scalar: if x10 ne -1 then qw1(x10) = ( qw0(x10+5120) + qw0(x10-5120) )/2
pass1:  print,'near maximum real signal: '
        print,r11
        print,'clipping value: '
        print,2*r11
        print,'number of clipped points: '
        print,n_elements(x10)
        print,'# points remaining above cliping value: '
        print,n_elements(where( qw1 gt 2*r11 ) )
        print,' '

        print,'qw1'
  tvscl,qw1 <2*r11


;*****make qw2
smooth = median(qw1,3)
res1 = qw1 - smooth
res2 = qw1 - smooth

r20 = mean(res1)
r21 = stddev(res1)
x20 = where( res1 gt (r20+sdc1*r21) OR res1 lt (r20-sdc1*r21) )
res2(x20) = ( res1(x20+10240) + res1(x20-10240) )/2
res3=res2
        print,'mean of residual 1: '
        print,r20
        print,'standard deviation of residual 1: '
        print,r21
        print,'number of cropped points: '
        print,n_elements(x20)
        print,' '
        print,'qw1.5'
  tvscl,res2+smooth <2*r11
```

```
r22 = mean(res2)
r23 = stddev(res2)
x21 = where( res2 gt (r22+sdc2*r23) OR res2 lt (r22-sdc2*r23) )
res3(x21) = ( res2(x21+10240) + res2(x21-10240) )/2
        print,'mean of residual 2: '
        print,r22
        print,'standard deviation of residual 2: '
        print,r23
        print,'number of cropped points: '
        print,n_elements(x21)
        print,'qw2'
  tvscl,res3+smooth <2*r11


qw2 = res3 + smooth

;*****determine line rotation angle
a = total(qw2(*,row1:row1+20),2)/21.
b = total(qw2(*,row2-20:row2),2)/21.
a = median(a,3)
b = median(b,3)
x30 = mean(a)/mean(b)
a1 = a
b1 = b*x30
cross_correlate,a1,b1,offset,corr
th30 = (offset/(row2-row1)) * (180./!pi)
        print,'offset angle'
        print,th30
        print,' '

qw3 = rot(qw2,th30,/cubic)
tvscl,qw3
print,'qw3'

;*****make qw4
as1=median(total(qw3,1)/1024.,3)
as2=total(qw3(*,row1+20:row2-20)/(row2-row1-40),2)
as3=qw3
for i=0,1023 do as3(i,*)=as1
for i=0,499 do as3(*,i)=as2*as1(i)
asx1=total(qw3(*,row1+20:row2-20))/total(as3(*,row1+20:row2-20))
as3=as3*asx1
asr1=qw3-as3
asr2=qw3-as3

r40 = mean(asr1)
r41 = stddev(asr1)
```

```
x40 = where( asr1 gt (r40+sdc3*r41) OR asr1 lt (r40-sdc3*r41) )
asr2(x40) = ( asr1(x40+10240) + asr1(x40-10240) )/2
qw4 = asr2 + as3
        print,'mean of residual 1: '
        print,r40
        print,'standard deviation of residual 1: '
        print,r41
        print,'number of cropped points: '
        print,n_elements(x40)
        print,' '
        print,'qw4'
  tvscl,qw4
  wait,1

;*****make qw5
qw5 = qw4(*,row1+20:row2-20)
window,21,xs=1024,ys=row2-row1-40
tvscl,qw5
        print,' '
        print,'qw5'
wait,1

;*****make qwspec,qwx
qwspec=total(qw5,2)/(row2-row1-40)
window,22,xs=1024,ys=500
plot,indgen(1023),qwspec,xr=[0,1023]
resx=qw-qw5
qwx=qw5


return
end
```

Appendix 2

Procedure "combine"

This IDL procedure, combine, was written to process the field lamp data taken with the portable spectrometer. Because the spectrometer had a low maximum intensity, both saturated and unsaturated spectra were collected. This procedure scales up the unsaturated spectra so that they have the same vertical scale as the saturated spectra. It then makes a copy of the saturated spectra and replaces them with the scaled-up unsaturated spectra in the regions where the saturated spectra are saturated. Finally, the procedure makes a more accurate wavelength scale for the spectra based on an input wavelength fitting and linearizes the spectra to that scale.

```
pro combine,A,B,E,la,lb,lc

;COMMAND-LINE VARIABLES
;A = input unsaturated spectrum
;B = input saturated spectrum
;E = output combined, linearized, and wavelength-limited spectrum
;la = input non-linear wavelength vector
;lb = input linear wavelength vector
;lc = output linear wavelength-limited wavelength vector

;INTERNALLY USED VARIABLES
;x = region where B is saturated
;y = region where B is unsaturated
;z = region where lb is less than 3500
;Abar = average value of A in region y
;Bbar = average value of B in region y
;m = scaling factor multiplied by A to scale it up to B
;C = combined but unlinearized spectrum
```

```
;D = combined and linearized spectrum

;SCALE-UP UNSATURATED SPECTRUM
y = where(B lt 3500)
Abar = mean(a(y))
Bbar = mean(B(y))
m = Bbar / Abar

;REPLACE SATURATED REGIONS OF B WITH SCALED-UP A
x = where(B gt 3900)
C = B
if mean(x) eq (-1) then goto, linearize
C(x) = m*A(x)

;CHECK REPLACEMENT
window,20
loadct,13
plot,C
wait,3.33
oplot,B,color=90
wait,3.33
oplot,x,A(x)*m,color=72
wait,3.33

;LINEARIZE COMBINED SPECTRUM AND LIMIT WAVELENGTH TO ABOVE
3500 A
D = spline(la,C,lb)
z = where(lb lt 3500)
E = D(max(z):(n_elements(D)-1))
lc=lb(max(z):(n_elements(lb)-1))

;DISPLAY FINAL SPECTRUM
window,20
loadct,13
plot,lc,E

return
end
```