

# NIGHTGLOW: An Instrument to Measure the Earth's Nighttime Ultraviolet Glow - Results from the first Engineering Flight

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## Abstract

We have designed and built an instrument to measure and monitor the "nightglow" of the Earth's atmosphere in the near ultraviolet (NUV). In this paper we describe the design of this instrument, called NIGHTGLOW. NIGHTGLOW is designed to be flown from a high altitude research balloon, and circumnavigate the globe. NIGHTGLOW is a NASA, University of Utah, and New Mexico State University project. A test flight took place from Palestine, Texas on July 5, 2000, lasting about 8 hours. The instrument performed well and landed safely in Stiles, Texas with little damage. The resulting measurements of the NUV nightglow are consistent with previous measurements from sounding rockets and balloons. The results will be presented and discussed.

Keywords: cosmic-rays, UHECR, EUSO, OWL, Fly's Eye, HiRES, AGASA

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## 1 Introduction

We are working on a program of balloon-borne observations of the near ultraviolet (NUV) light produced in the Earth's upper atmosphere, as well as observations of man-made and reflected light in the same regime. Surprisingly few measurements have been made in this range at night, although there are measurements from a few sounding rockets, [1], [2], [3] and an Italian balloon instrument [4]. These measurements are important for not only understanding the chemistry of the upper atmosphere [5] (and its changing characteristics) but because they form the background against which giant air showers from cosmic-rays are observed by the fluorescence technique [6]. In order to study the near ultra-violet (NUV) light levels in the atmosphere and their time variability over several weeks and months, NIGHTGLOW was designed to be flown at high altitudes for long durations. In this paper we report the results of our engineering flight.

## 2 Science Goals

Cosmic-ray particles constantly bombard the Earth from all directions, and with surprisingly high energies. Some of these have been observed at energies exceeding  $10^{20}$  eV [7]. For the most part, these particles are seen with one of three techniques: by directly measuring the electrons, positrons, and muons in the airshower they produce; by seeing the flash of Cherenkov light produced by the particles traveling faster than the speed of light in the atmosphere; or by observing the nitrogen fluorescence from the excited air molecules as the showers traverse the atmosphere. The only fluorescence detectors are the Fly's Eye [8], and its successor, HiRes [9]. The ground-based particle-detection technique is employed by Volcano Ranch [10], Havarah Park [11], and the AGASA array [12], among others. Within the past 10 years, AGASA, Fly's Eye, and HiRes have reported a few high-energy cosmic-ray primaries above  $10^{20}$  eV. These particles - if they are real - must be coming from a very local source ( $< 50$  Mpc), otherwise they would interact with the cosmic microwave background, lose energy, and pile-up below  $10^{20}$  eV, where the cross section for interacting with the microwave background falls. The cutoff of  $10^{20}$  eV is referred to as the the Griesen-Zasepin-Kushman (GZK) cutoff, after the first physicists to point out this effect. An alternative explanation other than a local source (which has not been identified) is some exotic particle or decay of an exotic relic from the big bang. In any case, it is crucial to our understanding to determine if these events are real. Since Fly's Eye and HiRes detect these air showers via nitrogen fluorescence, it is important to understand fully the UV background against which the particle showers are seen.

NASA (and ESA) is supporting an ISS mission called EUSO (the Extreme Universe Observatory,[18]), which will be used to detect ultra-high energy (UHE) cosmic-rays, at energies above  $10^{19}$  eV. In addition, a future free-flyer mission, the Orbiting Wide-angle Light collector (OWL, [19]) is being planned with even larger aperture and greater sensitivity. These mysterious UHE cosmic-ray particles interact in the Earth's atmosphere and excite the nitrogen, which then fluoresces in the near ultraviolet NUV (330 - 400 nm). An air shower from a primary of this energy produces as much light as a 40-Watt light bulb, moving at the speed of light through the atmosphere. EUSO (or follow on experiments such as OWL) may detect these rare particles ( 1 per km<sup>2</sup> per century!) by imaging their tracks from space, in the wavelength range 330 - 400 nm, with an instantaneous aperture approaching a million square kilometers. As a prelude to any observation from space, it is necessary to understand what other emissions occur in this same wavelength range that will be a background contribution to the primary fluorescence signal, for example man-made lights, and what their variability is. Previous measurements are discussed in [13]. NIGHTGLOW is a balloon instrument with three telescopes that will look at NUV light reflected from the Earth's surface and at light produced high up in the atmosphere. It's design is discussed below. As described by Meier [5], molecular collisions in the upper atmosphere result in excitation of the Chamberlain bands in N<sub>2</sub>. These emissions cover the wavelength range of 300 - 400 nm as shown in Figure 1 -

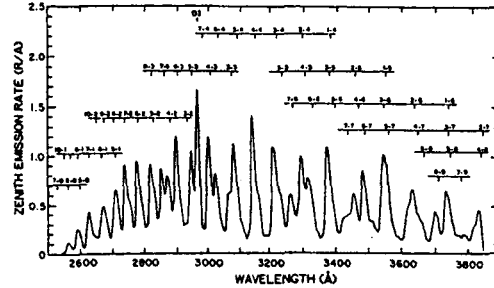


Figure 1: The NUV spectrum as measured by Hennes. We are interested in the 3000 - 4000 Angstrom regime.

taken from a paper by Hennes [1]. These emissions are time varying [14], and there may be some evidence that they have a wavelike structure. The flights by Greer et al. [15] show evidence that this emission occurs in a layer in the upper atmosphere at an altitude between 80 and 100 km.

### 3 Instrument Design

NIGHTGLOW consists of a balloon-borne platform for a fixed nadir-viewing telescope and a suspension frame for two rotating telescopes. The nadir-viewing telescope provides a fixed reference measurement. The rotating telescopes allow viewing of the NUV emissions from various sources and locations, including the important region between 80 - 100 km - well above the balloon at float, and the horizons, as well as the light reflected from the ground or produced by humans. Ground measurements are not adequate because of ozone absorption in the middle atmosphere and are also difficult to make and model due to pollution, smog, cloud cover, etc. In order to avoid contamination from aurora, it was decided that a mid-latitude flight was optimum. NIGHTGLOW was designed to be lightweight and low power, to enable long duration flights, potentially even around-the-world. This would enable us to test for time variability of the background. In its flight configuration with the instrument and ancillary flight electronics from NSBF, the suspended weight (without ballast) is 1740 pounds. With a simple approach, and using mainly off-the-shelf components, the NIGHTGLOW power was kept to only 31 Watts. Such a low power design enables NIGHTGLOW to be run entirely off lithium batteries - even for a 20-day around-the-world flight. Figure 2 shows a schematic view of the instrument and Figure 3 shows a picture of the instrument as assembled for the test flight outside the hangar in Palestine, Texas. For the around-the-world flight, there will be an array of 8 solar panels (each 122 cm x 122 cm) to provide power to

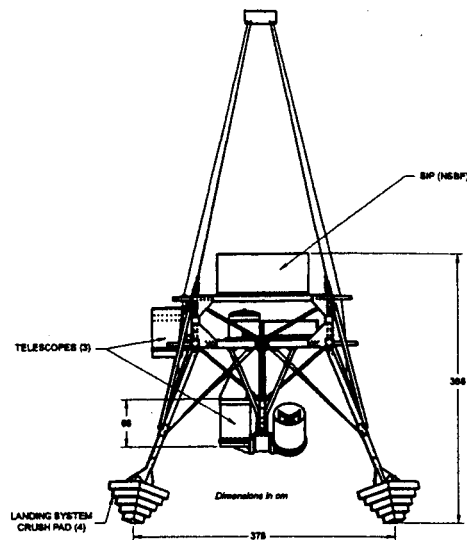


Figure 2: The NIGHTGLOW instrument schematic design.

the NSBF Science Instrumentation Package (SIP) electronics.

### 3.1 Optics

The design was based as much as possible on using parts identical to the HiRes experiment. The instrument in its long duration balloon (LDB) configuration has three identical Newtonian telescopes. Each has a 14 inch (35.5 cm) diameter primary mirror (spares from HiRes) with a 19 inch (48.3 cm) focal length ( $f/1.4$ ). The mirror reflectivity in the UV is 99%. At the focal point is a "spider" assembly of aluminum that holds a UV filter, a beam splitter, and two Phillips XP3062FL photomultiplier tubes (PMTs) mounted at right angles to each other. This assembly blocks 11% of the incoming light. The filter (same one used by HiRes) has a bandpass of  $T > 10\%$  between 300 - 400 nm, peaking at 84% at 350 nm (see Figure 4).

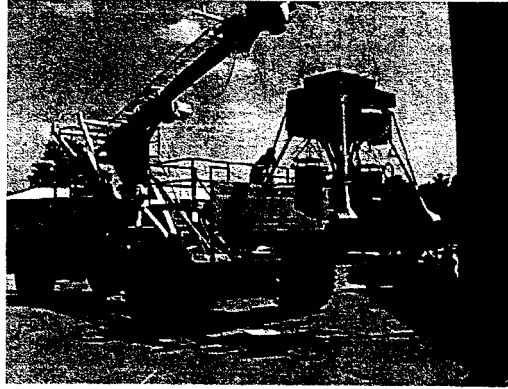


Figure 3: NIGHTGLOW hanging from the launch crane in Palestine, Tx.

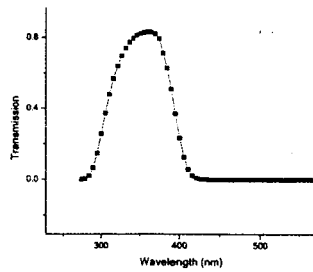


Figure 4: The UV filter bandpass, peaking at 350 nm. The University of Utah uses this same filter for the Fly's Eye experiment.

The incoming light is split with 10% going directly onto one PMT and the remaining 90% going through the UV filter. With this split, the relative signals in both PMTs should be approximately the same, meaning identical electronics processing chains can be used. The opening angle of each telescope is 3 degrees and at float altitude (100 kft) views approximately  $1 \text{ km}^2$  on the ground. This is intended to match (approximately) what EUSO and OWL will view from orbit. It was intended to fly as near as possible to a new moon to avoid contamination from (reflected) moonlight. One of the issues to be addressed during a long duration flight is how the NUV light level changes with the phase of the moon, and how that will affect (ultimately) any spaced-based instrument live time.

### 3.2 electronics

Based on extrapolations from the Fly's Eye and HiRes [8-9] instruments in Utah, it was estimated that the expected UV signal level of the "background" will be somewhere around  $44 \text{ photons}/\mu\text{sec}$  (scaling from their aperture to ours). All designs (optics and electronics) were driven by this expectation. NIGHGLOW makes a direct DC measurement of the incident (and only very slowly varying) light level. That is to say, the photomultiplier tubes are direct coupled at the anode outputs and no photon counting is employed. The visible and UV light is detected with the Phillips photomultipliers and fed directly into a current integrator. We use the same photomultiplier tubes designed by Phillips for the Fly's Eye experiment in Utah, the XP3062FL. These have a bi-alkali photocathode with a peak quantum efficiency of 25% at 420 nm. The entrance window is lime glass which transmits  $> 10\%$  of the incident light for wavelengths  $> 300 \text{ nm}$ . Each PMT has a 5 MW resistor divider chain, and operating at our nominal (negative) 850 Volts, draws 80 mA of current. The gain at 850 Volts is approximately 1628 Amps/Watt, temperature corrected to  $-30 \text{ deg C}$ , the temperature expected for operation at float altitude. Each PMT was scanned in the laboratory at Univ. of Utah with a fixed Xenon flasher, emitting a precisely known photon flux. This is the same calibration flasher, etc. used by the Fly's Eye and HiRes groups for their air shower detectors. The PMT output from 15000 flashes is summed and digitized and the PMT response is then calculated. This allows the response to be calculated to better than 1%. In addition, each PMT was tested separately for response at  $-30 \text{ deg C}$ , and in vacuum down to pressures of 5 Torr (equivalent to an altitude of 120,000 feet or 40 km). The PMT's outputs are direct coupled to a Burr-Brown integrator unit (ACF2101). This unit is operated with an external integrating capacitor of  $0.05 \mu\text{F}$  and an offset current reference at the input. This design gives us control over the gain and working range of the instrument. The integrator is gated on with a variable width gate pulse, controlled by the on-board CPU. The normal operating width of the gate pulse is between 100 msec and 125 msec. After the integration cycle, a Diamond MM-32 A/D converter (16 bit) digitizes the output and then the integrator is reset. The integrator gate width and an offset voltage are both used to adjust the baseline signal level and the dynamic range should we need to do so. The integrator can swing between -10 Volts and 0 Volts and integrates

up toward zero from its normal (negative) baseline. The current source was set up so that the offset voltage was -6.34 volts for a 125 msec integration time and no signal out from the PMT (i.e. a "dark" reading). As the PMT signal rises, the output voltage rises from this baseline, with 100 mVolts corresponding to an input charge of  $5 \times 10^{-9}$  Coulombs, or a current of 40 nAmps. The PMT operating at -850 Volts has a gain of 1628 Amps/watt (temperature corrected to  $-30 \text{ deg } C$ , varies by 0.1% per  $\text{deg } C$ ), so this corresponds to an incident light intensity of  $2.46 \times 10^{-11}$  Watts (at 350 nm), or  $4.32 \times 10^7$  photons per second (43 photons/ $\mu\text{sec}$ ). The entire electronics is built around a PC104 format 386 PC, Comm port card, solid-state memory, and a floppy drive (for ground use). A UV LED (350 nm) from Nichia is used on-board to calibrate periodically, but is not actively temperature stabilized. Rather, it was mounted on an aluminum "leg" that should be near  $-30 \text{ deg } C$  during the flight. Also on board is a magnetic compass that provides the payload magnetic heading, as well as pitch and roll angles of the gondola, accurate to better than 0.1 degree. These readings are used to correct the pointing of the telescopes. There are 3 GPS receivers on board. The GPS provides position (latitude and longitude and UTC) and altitude information, as well as payload speed. An infrared sensor is mounted looking downward and is used to detect cloud cover under the payload. It operates in the 8 - 14 micron wavelength range. In addition, satellite cloud cover data is also available for post-flight analysis.

### 3.3 Software

The on-board software was designed from the beginning to allow autonomous operation throughout the potential 20-day flight. One of the main tasks performed is calculating the current local sunrise and sunset times based upon the GPS position information. The instrument automatically switches states from a stand-by DAY mode when the sun is up, to an active NIGHT mode after sunset (and twilight). A preprogrammed viewing cycle starts at night, with the rotating telescopes moving in opposite directions to prevent the payload from swinging. At each target position several readings (the default is three, but the number is programable) are taken of the light levels. All the data is telemetered to the ground through the NASA TDRSS system and stored on-board. If the payload is successfully recovered this provides a complete data backup without any possible telemetry dropouts. For our engineering flight, all data was telemetered using a line-of-sight transmitter only.

### 3.4 Mechanical

The NIGHTGLOW structure consists of two main decks (a SCIENCE deck and a SIP deck) made from 4"x4" and 3"x3" aluminum box beams. These are riveted together with gussets in the corners. Solid end fittings are bolted to the top deck and provide an attachment for (four) lift rings. This structure can be seen in Figures 2 and 3. Suspended from the bottom of the SCIENCE deck is a KEEL structure that provides a stable support platform for the Phytron stepper

motor and controller and the two counter-rotating telescopes. The motor is geared down through a transmission assembly that provides a 300:1 reduction in step size. The pointing accuracy for the telescopes is 0.1 degree. It is desired that the three telescopes be co-aligned when the two rotating ones are pointing to the nadir position. We found that it was possible with standard machining techniques and shims to achieve a 0.1-degree alignment. This gives an error in the co-alignment of the field-of-views of at most 50 meters (on the ground) out of a 1 km area. The telescopes move in a plane, scanning from 45 degrees off of vertical (the 28 million cubic foot balloon blocks the zenith cone) through a downward arc. Every 15 degrees the moving telescopes stop and we take a reading of the UV light level. There is no swivel or pointing mechanism in the lift train above the payload - no attempt is made to hold a fixed position. The various on-board sensors allow corrections for tilt, etc. on the ground and give knowledge of where each telescope was pointing when a measurement was taken.

Landing legs are attached by ball-and-socket fittings to the lower of the two decks for ground support and landing after release from the balloon. Crush pads are attached to the bottom of the legs for cushioning. The legs angle out so as not to block the field-of-view and to provide additional stability, especially upon landing.

## 4 Test Flight

The instrument was shipped to the National Scientific Balloon Facility in Palestine, Tx. (latitude of 31.4 N). There it was flown for an eight-hour overnight engineering flight on July 5, 2000 (four days past the new moon on July 1, 2000). The moon set at approximately midnight and sunrise the next day was at 6:23 am local time. The launch occurred at 7:49 PM local time and the payload reached a float altitude of 100,000 feet at 10:30 PM local time. Local sunset was at 8:32 PM and twilight lasted until 10:00 PM. The on-board computer turned the instrument on at 9:59 PM. The flight trajectory took the payload to the west, eventually covering 333 nautical miles, averaging about 40 miles per hour. Cutdown occurred at 04:15 AM on July 6 and the payload was recovered near the small town of Stiles, Tx. (see map, Figure 5) The flight path took the instrument over the small town of San Angelo, Texas. The flight was terminated prior to sunrise due to telemetry range limitations. The only significant damage to the payload was that two of the landing legs were broken.

### 4.1 Results

For the test flight, only one rotating telescope was mounted on the instrument, the other was replaced with a dummy mass to give the same moment of inertia as the actual telescope. No fixed telescope was flown either in the event of a catastrophic landing. With one telescope two photomultiplier tube channels were available. On the ascent, one channel of one integrator failed, leaving us



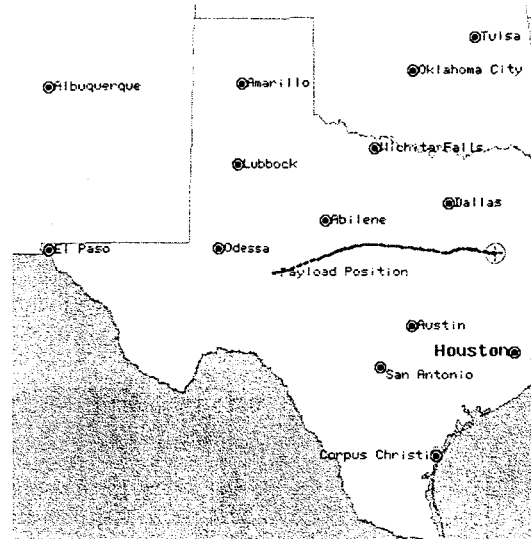


Figure 5: Map showing the flight trajectory. The launch site is Palestine, Tx. and the recovery site is Stiles, Tx.

with only one measurement and no redundancy. Fortunately, that remaining channel behaved well for the entire flight. Figure 6a shows a sample plot of the raw PMT output versus time, and Figure 6b shows an expanded view. This portion of the data was taken after the moon set during the early morning hours of July 6. The large spike in the data corresponds to an unexplained, momentary shift in the integrator baseline. This point has been removed from the final data analysis.

Figure 7 shows the same data as a function of telescope position. The positions where the rotating telescope stops for a light reading are numbered L1 - L19 (L1 and L19 are both 45 degrees from the zenith, and L10 is straight down). Figure 8 shows the data after averaging over the telescope position for three hours of total darkness. The error bars in the plot are statistical. One can see from Figure 7 that the scatter in the data is greater for positions 10 - 15; hence the error bars for those positions are larger.

After converting the output current to a photon flux (using the temperature corrected PMT gain) and then correcting for the efficiencies of the optics and viewing aperture (the optics of the telescope gives a geometrical factor of  $3.7 \times 10^{-4} m^2 - sr.$ ), the calculated nightglow level is found, as shown in Figure 9.

Several important features can be seen in Figure 9. First of all, two peaks can be seen at positions L4 and L16, 45 deg and 270 deg. These positions point to the horizons, i.e. the telescopes are parallel to the ground. Position L4 points roughly to the east and L16 to the west. (During the flight the tilt of the gondola was never more than 0.5 degrees.) In these positions the instrument is looking

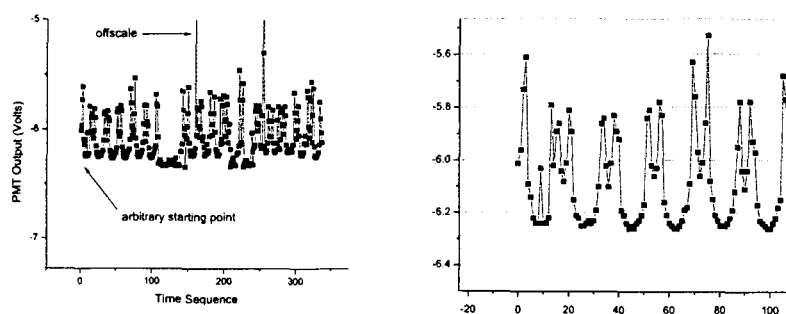


Figure 6: (a-left panel) Raw data taken during the flight showing the output from the photomultiplier in a time sequence. (b-right panel) A blowup of data from the previous plot showing the detailed structure of the signal.

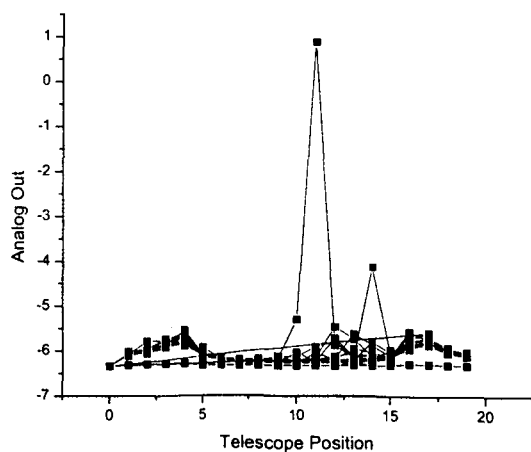


Figure 7: The data from the dark portion of the flight (i.e. no moon) folded onto itself as a function of telescope viewing position. The viewing positions are labeled 1 - 19, with the middle position (10) being nadir pointing.

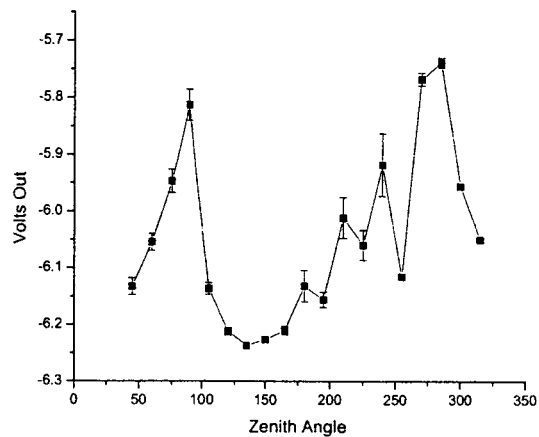


Figure 8: The baseline corrected, position averaged data from the flight.

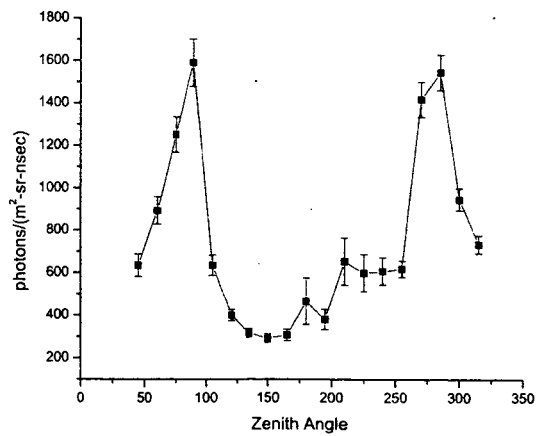


Figure 9: The data converted from engineering units to real units, photons/( $m^2 - sr - nsec$ ).

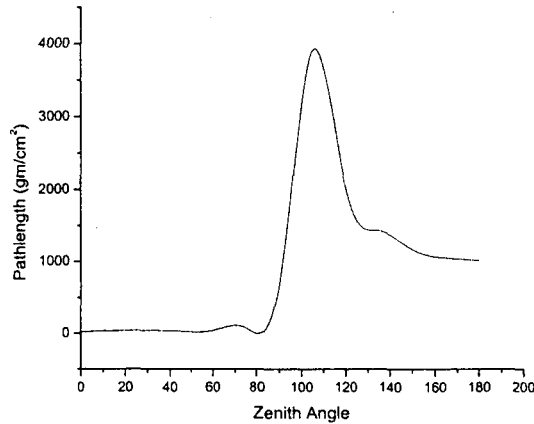


Figure 10: The pathlength for viewing through the atmosphere from the payload, using the standard atmosphere.

through increased atmosphere, toward the Earth's limb.

For nightglow measurements relevant to UHE cosmic-ray air showers observed from space, the primary regions of interest are two telescope positions: the nadir position (180 deg) and the 45 deg (315 deg) position. The second observation from Figure 9 is then that the nightglow from the nadir position is less than from the 45 deg (315 deg) degree position. This is not simply due to looking through a shorter pathlength through the atmosphere. This arises because the telescopes at 45 deg (315 deg) are viewing the region of the atmosphere above 80 km where much of the NUV light is produced [5]. The 180 deg level is approximately 1/2 of the 45 deg (315 deg) value.

Taking the 45 deg and 315 deg values and averaging them together, we get a value of  $691 \pm 34 \text{ photons}/(m^2 - sr - nsec)$  for the upward looking nightglow. Upon averaging the values from the three lowest viewing positions (165 deg, 180 deg, and 195 deg), we get a value of  $353 \pm 41 \text{ photons}/(m^2 - sr - sec)$ . These results are discussed more in the next sections. Referring back to the data of Greer et al., the existence of an emitting layer of atmosphere (at 90 km) above the payload (at 30 km) can be demonstrated. Simply normalize the measured values to compensate for the amount of atmosphere being viewed at each telescope position. Figure 10 shows the calculated (density x pathlength) correction calculated from a standard atmosphere [16] profile, and Figure 11 shows the corrected nightglow data versus zenith angle. It is clear that the largest NUV background signal is observed from above the payload, in a region of low density. Unfortunately, the NIGHTGLOW flight was too short, and the instrument pointing too coarse to say more about this layer at this time. Future flights will hope explore this in much greater detail.

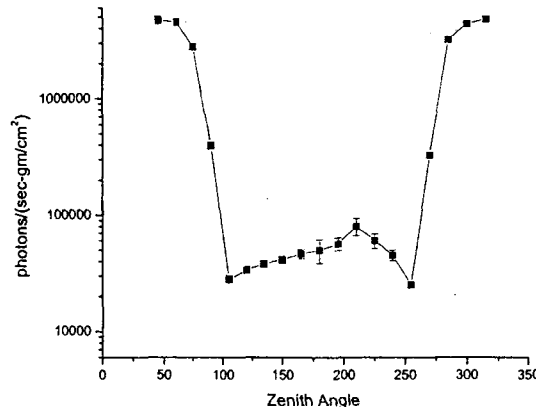


Figure 11: The corrected signal obtained by dividing by the pathlength in  $gm/cm^2$ . This demonstrates that the largest signal comes from the 45 and 315 degree positions - from a layer above the balloon.

## 5 Conclusions

After calculating the measured nightglow on our flight, corrections must be applied for zodiacal light and background starlight. We refer to data from Leinert et al. [17], which shows that these two corrections are roughly equal in magnitude. Using their data (Figure 12), and integrating between 300 and 400 nm (assuming a linear fit) each correction is calculated to be approximately  $240 \text{ photons}/(m^2 - sr - nsec)$ .

Subtracting this from the upward looking value of  $691 \text{ photons}/(m^2 - sr - nsec)$  yields a corrected upward looking value of  $210 \pm 34 \text{ photons}/(m^2 - sr - nsec)$ , and a total NUV background (combining upward and downward looking values) of  $563 \text{ photons}/(m^2 - sr - nsec)$ . Multiplying by the telescope geometry factor converts this to  $208 \text{ photons}/\mu sec$ .

For comparison to our data, we refer to the HiRes experiment, which has measured from the ground a background NUV intensity of 266 photons/microsecond with a geometrical factor 6 times larger than NIGHTGLOW. Their value of  $266/6 = 44.3$  is 4.5 times smaller than the value reported here. Part of the difference can be attributed to ozone absorption in the atmosphere, which the HiRes array is subject to when viewing NUV light produced in the upper atmosphere. At 330 nm the ozone absorbs up to 70% of the light. If the HiRes number is corrected for this absorption, it becomes 63 photon/microsecond. This is still a factor of three times lower than our value. This discrepancy is not understood at this time.

The Italian "BABY" balloon instrument [4] has flown twice from Sicily, once in 1998 and once in 2001. Their instrument only views the nadir direc-

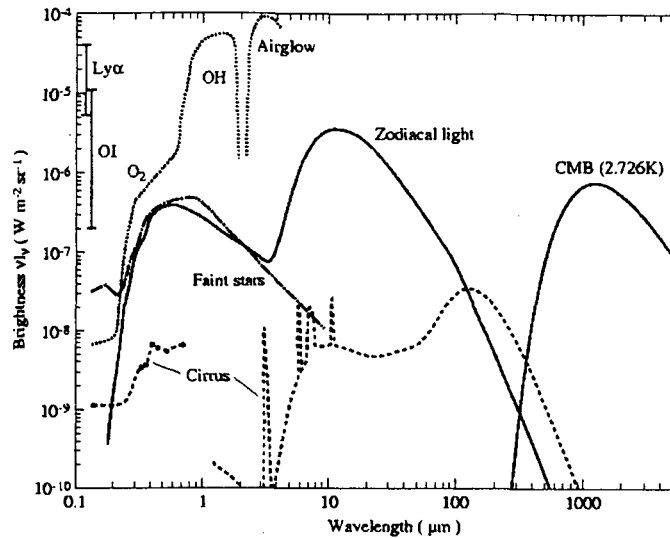


Figure 12: The contribution of the zodiacal and faint star background from Leinert et al.

tion. They report a value of  $400 \text{ photons}/(\text{m}^2 - \text{sr} - \text{nsec})$  for the background over the dark Mediterranean Sea waters. This is a lower value than the 564 measured by NIGHTGLOW, because they do not view the upward component in the atmosphere. However, our downward looking component is consistent with theirs,  $400$  vs.  $353 \pm 41 \text{ photons}/(\text{m}^2 - \text{sr} - \text{nsec})$ . This modest difference might be due to ground reflectivity as BABY flew over water and NIGHTGLOW flew over desert. The intensity reported from Hennes [1] is 278 R, or  $320 \text{ photons}/(\text{m}^2 - \text{sr} - \text{nsec})$ , which is consistent with BABY's and NIGHTGLOW's. Table 1 summarizes all these results. Unfortunately, NIGHTGLOW did not fly over any clouds during the test flight, so we have yet to explore the issue of light reflection off cloud tops. In addition, no conclusions about variability can be made based solely on such a short flight ( $< 8$  hours), with only 3 hours of dark data. Hopefully these issues can be explored more in future, long duration flights. Our final conclusion is that any spaced-based mission to look for UHE cosmic-rays, such as EUSO or OWL, will have to contend with a UV background of  $500 \text{ photons}/(\text{m}^2 - \text{sr} - \text{nsec})$  in the 300 - 400 nm range.

## 6 Acknowledgement

We would like to thank the crew of the NSBF for all their help in integrating the NIGHTGLOW payload and their excellent support on our test flight. Also, a special thanks to Bob Hull (NMSU), Deneen Ferro (GSFC), Stephen Holder

Table 1: Summary of near UV measurements

| Measurement | Value ( $photons/(m^2 - sr - nsec)$ ) | Comments                           |
|-------------|---------------------------------------|------------------------------------|
| Nightglow   | 353                                   | Nadir viewing component            |
| Nightglow   | 210                                   | Upward viewing component           |
| BABY        | 400                                   | Nadir viewing only                 |
| Hennes      | 320                                   | Rocket flight, corrected to zenith |
| HiRES       | 78                                    | Ground-based measurement           |

(GSFC) and Frank San Sebastian (GSFC) for all their hard work.

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