Calculated Photoelectron Flux Validation under Solar Minimum Condition using High-resolution Cross sections

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Introduction

Terrestrial low latitude Photoelectron flux spectrum observed by Atmospheric Explorer - E (AE-E) during a solar minimum condition has been compared with calculated photoelectron flux spectrum by Atmospheric Ultraviolet Radiance Integrated Code (AURIC, Strickland et al, 1999) using high-resolution photoabsorption and photoionization cross sections for N_2 and O. Comparison between theory and measurement shows convincing agreement in low energy regime (0 - 100 eV) at all altitudes in between 150 km to 300 km where photoelectron transport effects are negligible. Our comparison accounts well resolved peaks between 20 eV to 30 eV due to photoionization of N_2 and O at 25.2 eV and 27.2 eV, respectively, by the solar 304Å He II line. We also found the well-known large dip around 2.5 eV caused by the vibrational-rotational excitation of N_2. Our study suggests that the numerical calculation done in AURIC is not unreasonable based on the comparison between data and model except 0 - 5 eV energy range. For the high altitude and high latitude data-model comparison, it is expected to account for pitch angle distribution of photoelectron flux. In future, we will employ the data observed by Fast Auroral Snapshot Explorer (FAST) for high-energy regime comparison.

AURIC

- Atmospheric Ultraviolet Radiance Integrated Code.
- Calculate the thermospheric emission spectra from 800 to 10000Å.
- Major Inputs - photoionization and photoabsorption cross sections in both high- and low-resolution**; High-resolution solar EUV flux spectra; Geolocation, date, time.
- Major Outputs - photoionization, photodissociation, photoelectron energy loss (by excitation, ionization, and interaction with the ambient plasma), chemical reactions, emission through a variety of allowed and forbidden atomic and molecular transitions.
- High-res Photoionization and photoabsorption cross sections for atmospheric constituents N_2, O and updated solar spectrum in high-resolution (Soto et al., 2023). O_2 needs to be updated.
- High-res AURIC showed remarkable increment of ionization in electron density profiles at E-region (Sakib et al., 2023).
- Aim :
  - To validate calculated photoelectron fluxes, we compare AURIC results with high energy resolution photoelectron fluxes measured by the Photoelectron Spectrometer Experiments on board the Atmospheric Explorer E (AE-E) satellite [Lee et al., 1980].

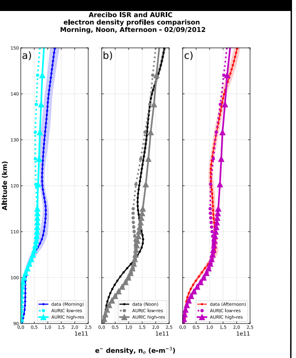


Figure 1 : Example of AURIC capability after utilizing high-resolution cross sections and solar irradiance in the model.

Photoelectron Flux and Source Function

- Flux : A concept incorporating density and velocity important for gas kinetics and macroscopic formalism is called "flux" of a scaler quantity. Example: energy flux, particle flux, or photoelectron flux.
- Photoelectrons : Electrons produce at upper atmosphere due to photoionization or electron flux emitted from atmospheric atoms/molecules by interaction with photons.
- Important absorption processes: Photodissociation, photoionization, dissociative photoionization.

$$O + h\nu \rightarrow O^+ + e^-$$
$$N_2 + h\nu \rightarrow N_2^+ + e^-$$
$$O_2 + h\nu \rightarrow O_2^+ + e^-$$

Example

Ionization of O by solar He+ emission at 304A

$$\text{Photon energy} = h\nu_s = \frac{hc}{\lambda_s} = \frac{12397}{304} = 40.78\ eV$$

Ionization into ground state of $O^+ = 13.62\ eV$

Excess energy $= 40.78 - 13.62$ eV $= 27.16\ eV$

– What happens to excess energy?

Kinetic energy of photoelectron

- Important source of secondary ionization and dayglow emission.
- Heat source for plasmasphere.

- $\pi F_0(\lambda)$ - Unattenuated solar flux of wavelength (λ)
- Most of the solar energy deposited below 100 km and insignificant except major geomagnetic storm or high/extreme solar condition
- AURIC uses a discrete version of solar irradiance spectrum $\pi F_0(\lambda_i)$ where λ_i refers to the i-th line and flux unit : photons $cm^{-2}S^{-1}$

$$\pi F(\lambda_i, z, \mu_s) = \pi F_0(\lambda_i) \exp[-\tau(\lambda_i, z, \mu_s)] \text{ ----------(1)}$$

So, optical depth,

$$\tau = \ln(\pi F_0) - \ln(\pi F)$$

Or in other words,

$$\tau = \tau(\lambda_i, z, \mu_s) = \sum_l \tau_l(\lambda_i, z, \mu_s) = \sum_{l,k} \sigma_{lk}^{photo}(\lambda_i) \int n_l(s)ds \text{ ----------(2)}$$

The production of an ionic or neutral state by absorption of photons from the flux $\pi F(\lambda_i, z, \mu_s)$ is given by

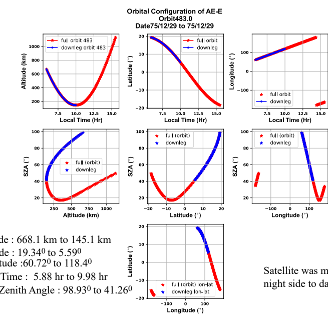
$$\delta P_{lki}(z, \mu_s) = n_l(z) \pi F(\lambda_i, z, \mu_s)\ \sigma_{lk}^{photo} \text{ ---------------(3)}$$

The accompanying expression for production of photoelectrons

$$\delta S_{lki}(z, \mu_s, h\nu_i - I_{lk}) = n_l(z) \pi F(\lambda_i, z, \mu_s)\ \sigma_{lk}^{photo} \text{ ----(4)}$$

So, photoelectron energy =Photon energy – Ionization potential energy. Equation 4 is used to specify the source function S_λ.

Atmospheric Explorer –E and AURIC comparison



- Altitude : 668.1 km to 145.1 km
- Latitude : 19.34⁰ to 5.59⁰
- Longitude :60.72⁰ to 118.4⁰
- Local Time : 5.88 hr to 9.98 hr
- Solar Zenith Angle : 98.93⁰ to 41.26⁰

Satellite was moving from night side to dayside.

Figure 2 : AE-E orbital configuration during a typical perigee pass on December 29, 1975.

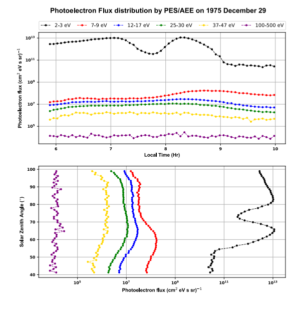


Figure 3 : Photoelectron energy spectra between 1 and 500 eV observed by photoelectron spectrometers (Doering et al., 1973) onboard AE-E as a function of local time and solar zenith angle.

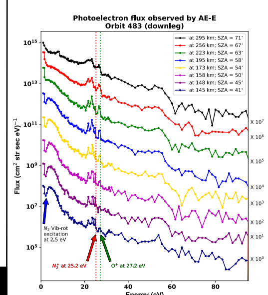


Figure 4 : Photoelectron flux distribution as as function of energy observed by PES instrument onboard AE-E at different altitudes in between 145 km to 295 km.

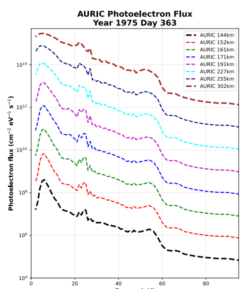


Figure 5 : Photoelectron flux distribution as as function of energy calculated in AURIC using updated high-resolution cross sections and solar irradiance.

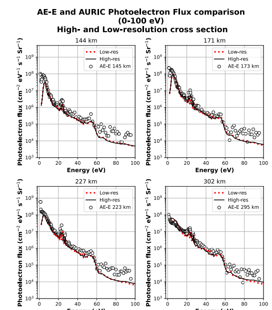


Figure 6 : Comparison between AE-E and AURIC photoelectron flux spectra at four different altitudes 144 km, 171 km, 227 km, and 302 km, respectively. White circles are the measurements by AE-E, solid black line represents AURIC runs with high-resolution updates, while, broken red line represents low-resolution AURIC runs.

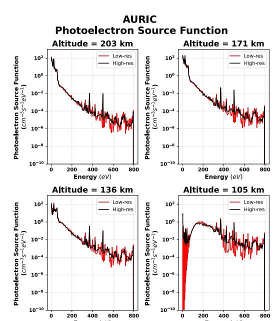


Figure 7: Photoelectron source functions vs energy are shown at an altitude 203 km, 171 km, 136 km, and 105 km when utilizing the high-resolution (black) and low-resolution (red) AURIC. The computations were made using a binned NRLEUV solar spectrum for low-resolution and the 0.01Å resolution solar spectrum for high- resolution.

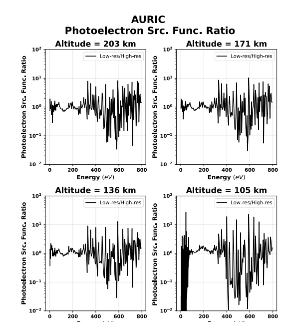


Figure 8: Photoelectron source function ratios vs energy are shown at an altitude 203 km, 171 km, 136 km, and 105 km. The ratios are taken with respect to the photoelectron source function calculated using the high-resolution cross sections: low-resolution/high-resolution.

Solar Minimum Condition

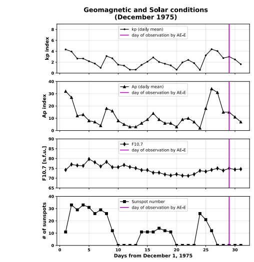


Figure 9: Geomagnetic & solar EUV conditions for the month of December 1975 (31 days).

Observational day condition:
- Kp is low < 4 ,
- Ap is low < 20 ,
- $F_{10.7}$ < 80 solar flux unit,
- Number of sunspots = 0.

A detailed description of these geomagnetic indices can be found in matzka et al., 2021. Local noon time observed $F_{10.7}$ cm solar radio flux is presented in this figure in solar flux unit.

(1 s.f.u. = $10^{-22}\ Wm^{-2}Hz^{-1}$)

Results and Conclusion

- Observation:
  - Below 200 km, well resolved peaks are observed in the spectrum corresponding to production of O+ and N2+ in various electronic state from photoionization of N_2 and O by solar He-II (304Å) radiation.
  - Vibration –rotation excitation of N_2 inelastic electron scattering is observed at 2.5 eV.
- Model:
  - AURIC prediction of PEF above 5 eV up to 60 eV is most consistent with data.
  - The photoelectron source functions are in general agreement at energies less than 200 eV; however, diverge at greater energies.
  - At 500 eV the low-resolution ratio decreases by at least an order of magnitude and then increase by over an order of magnitude at 650 eV.

Future work:

We will calculate PE fluxes at an upper boundary of 1000 km to the FAST (Pfaff et al., 2001) altitude of 3700 km without attenuation and neglecting plasmasphere effects (Woods et al., 2003).

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Acknowledgement

1. **National Science Foundation Grant No. 1849014.**
2. **Dr. Phil Richards, for providing AE-E data (private communication).**
3. **NASA Space Physics Data Facility for data availability.**

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