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Consequences of Cathodoluminescence for Cryogenic Applications of SiO2-based Space Observatory Optics and Coatings

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Properties of Cathodoluminescence for Cryogenic Applications of SiO_2-based Space Observatory Optics and Coatings

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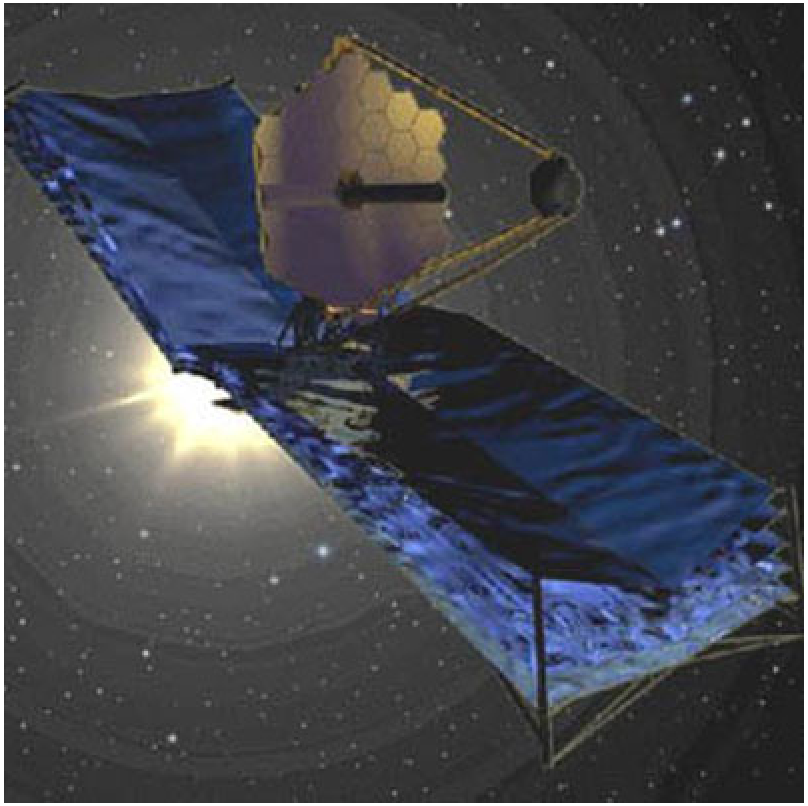
Outline

- Introduction
- Experimentation
- Results
- Considerations for Application
- Conclusions

Introduction

Today's space-based astronomical observatories:

- more complex and sensitive detectors
- reside in more extreme and remote environments
- larger and require open architectures
- operate at broader temperature ranges



Introduction

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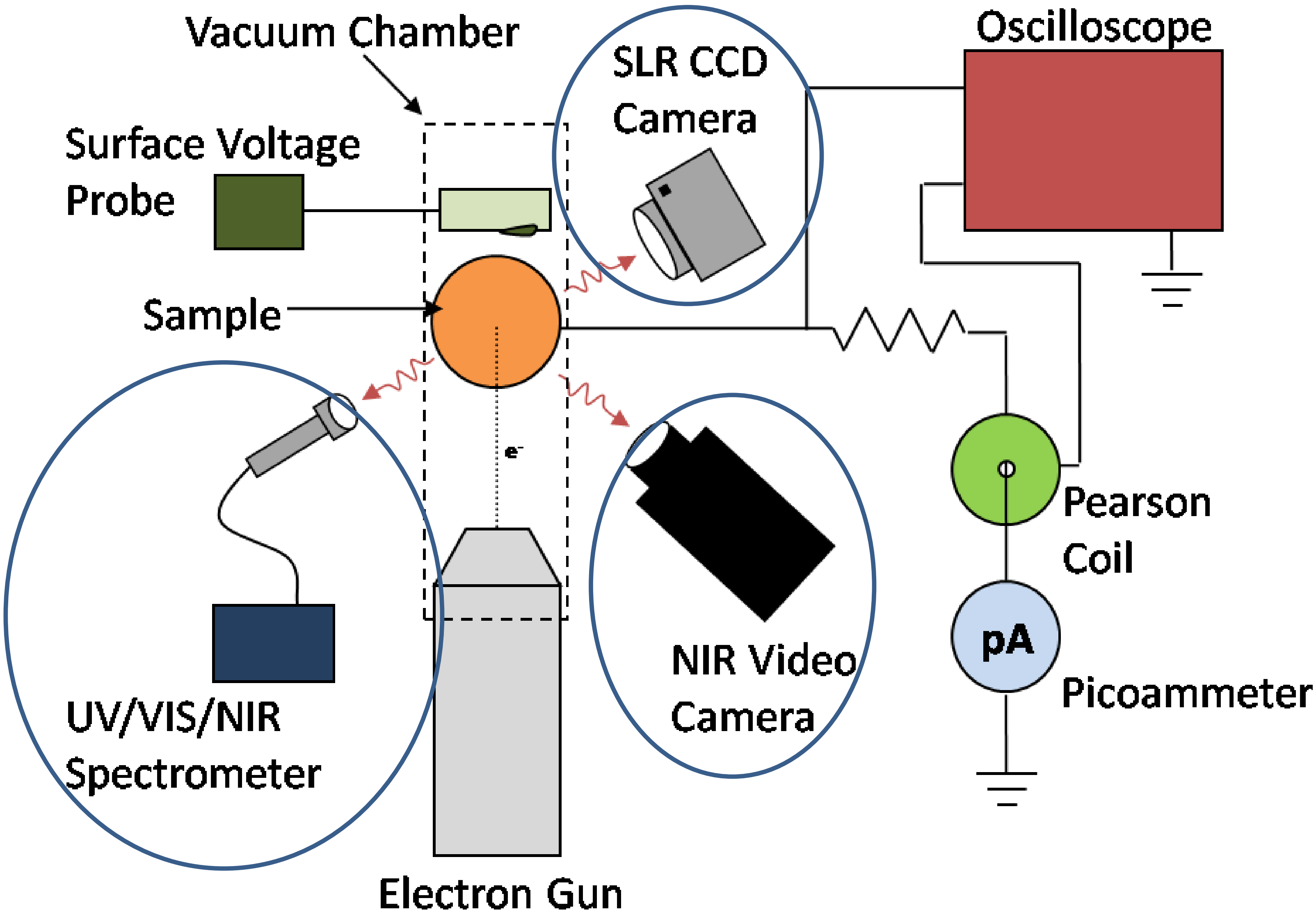
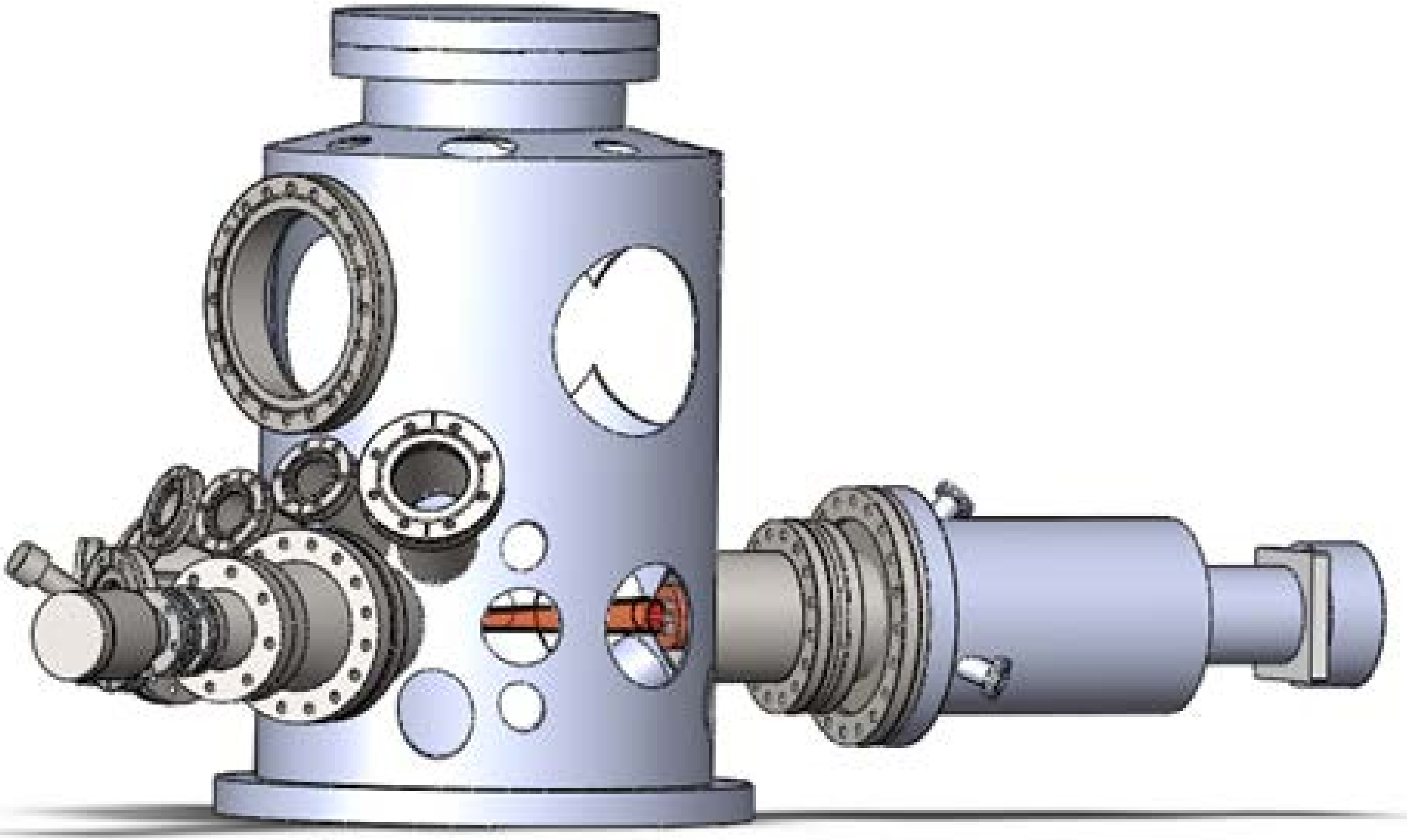
Experimentation



Experimentation



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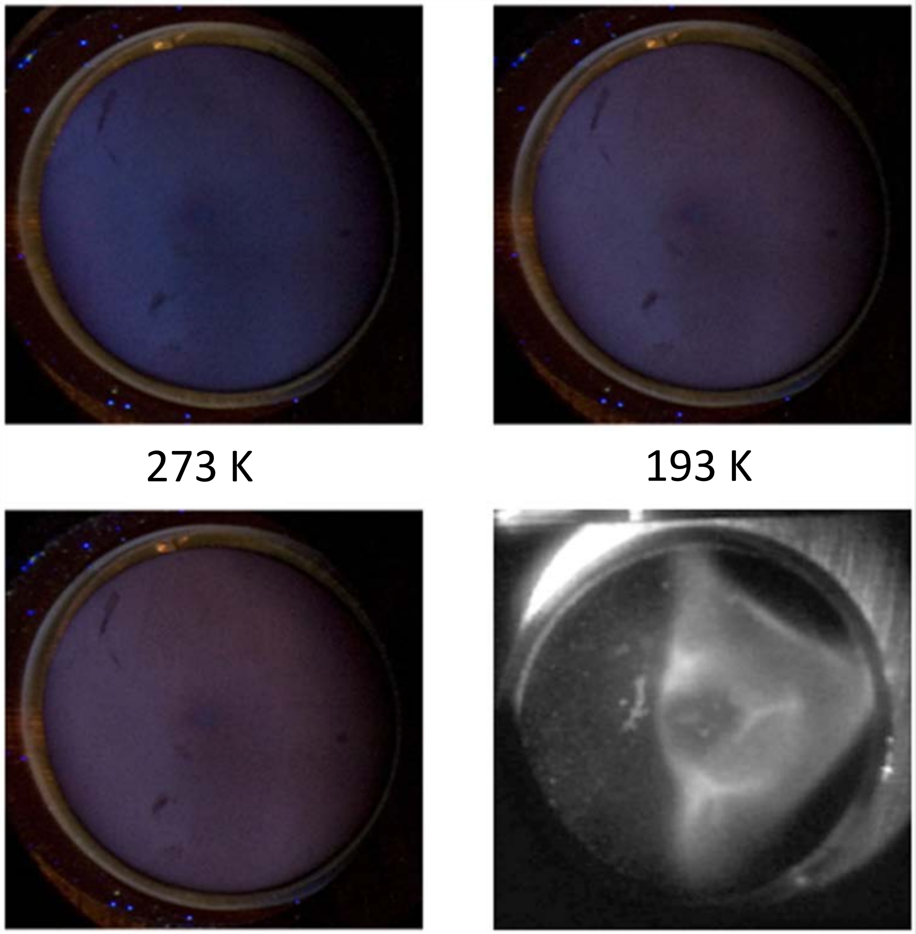
Results

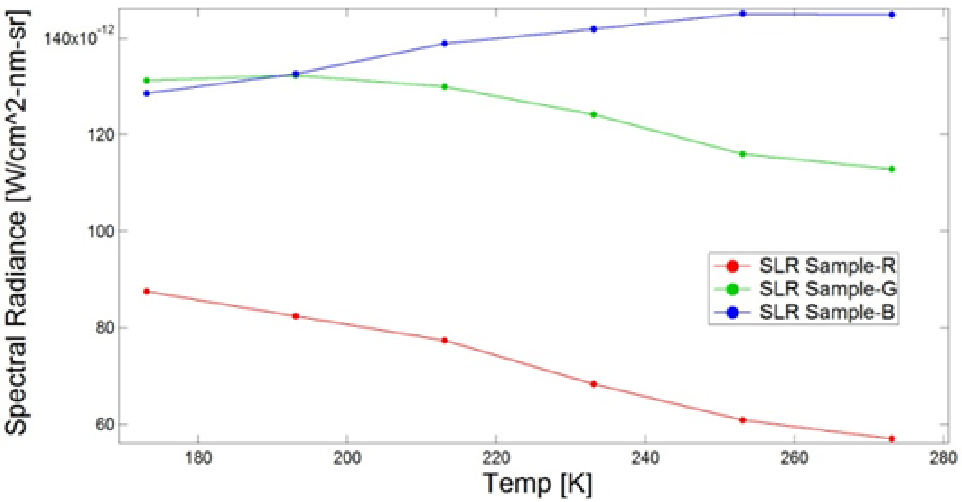


273 K

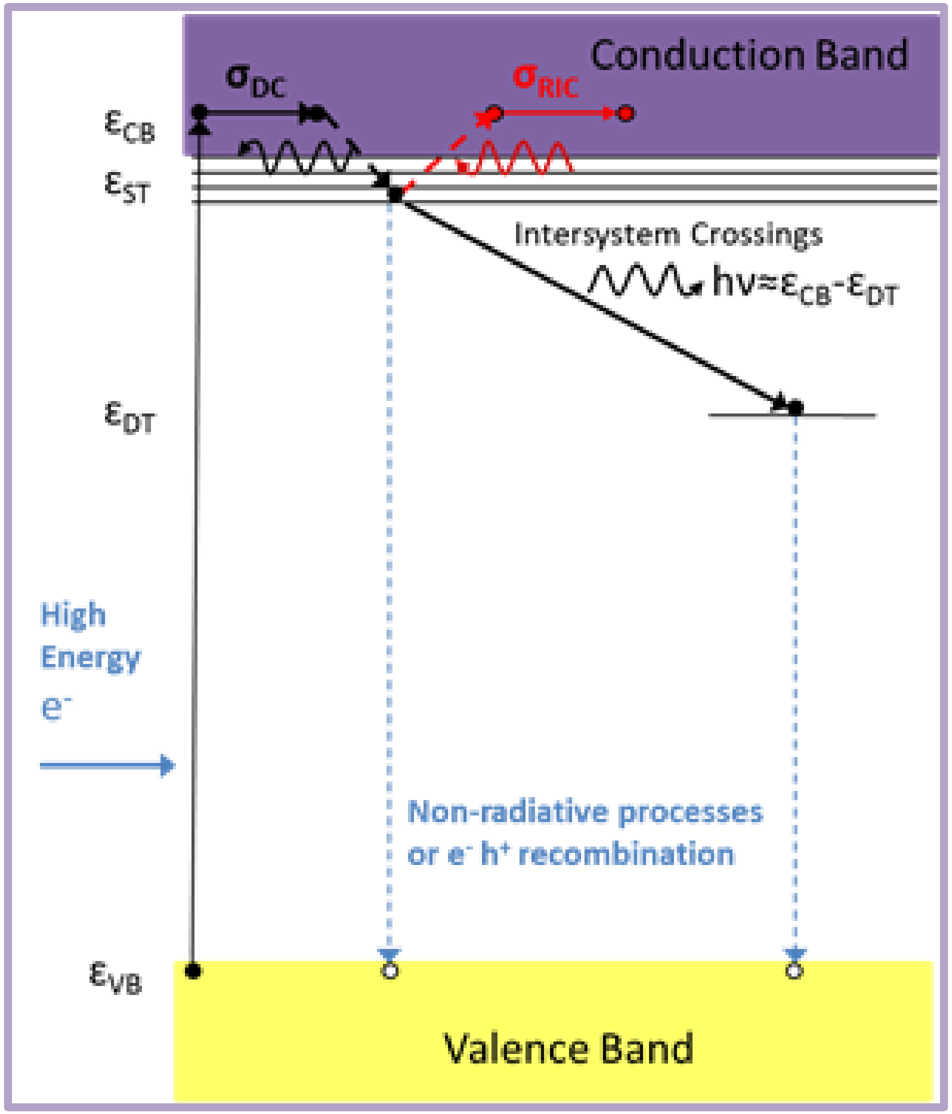
193 K

163 K

Distorted, defocused beam



Results



Proposed Model: Band Theory

1. incident high energy, charged particle undergoes a series of inelastic collisions exciting valence band electrons into the conduction band
2. excited electron rapidly decays to localized (shallow trapped) states, with a mean binding energy below the mobility edge.
3. electron in short-lived shallow trap states falls to longer lived deep trap states producing a photon

Results

Proposed Model

$$I_\gamma(J_b, E_b, T, \lambda) \propto \frac{\dot{D}(J_b, E_b)}{\dot{D} + \dot{D}_{sat}} \{[e^{-(\varepsilon_{ST}/k_B T)}][1 - e^{-(\varepsilon_{ST}/k_B T)}]\}\{[1 - \mathbb{A}_f(\lambda)][1 + \mathbb{R}_m(\lambda)]\}$$

I_γ: luminescence intensity
E_b: incident beam energy
λ: photon wavelength

J_b : incident current density
T: temperature
D: dose rate

$$\dot{D}(J_b, E_b) = \frac{E_b\, J_b[1 - \eta(E_b)]}{q_e \rho_m} \times \begin{cases} [1/L] & ;\ R(E_b) < L \\ [1/R(E_b)] & ;\ R(E_b) > L \end{cases}$$

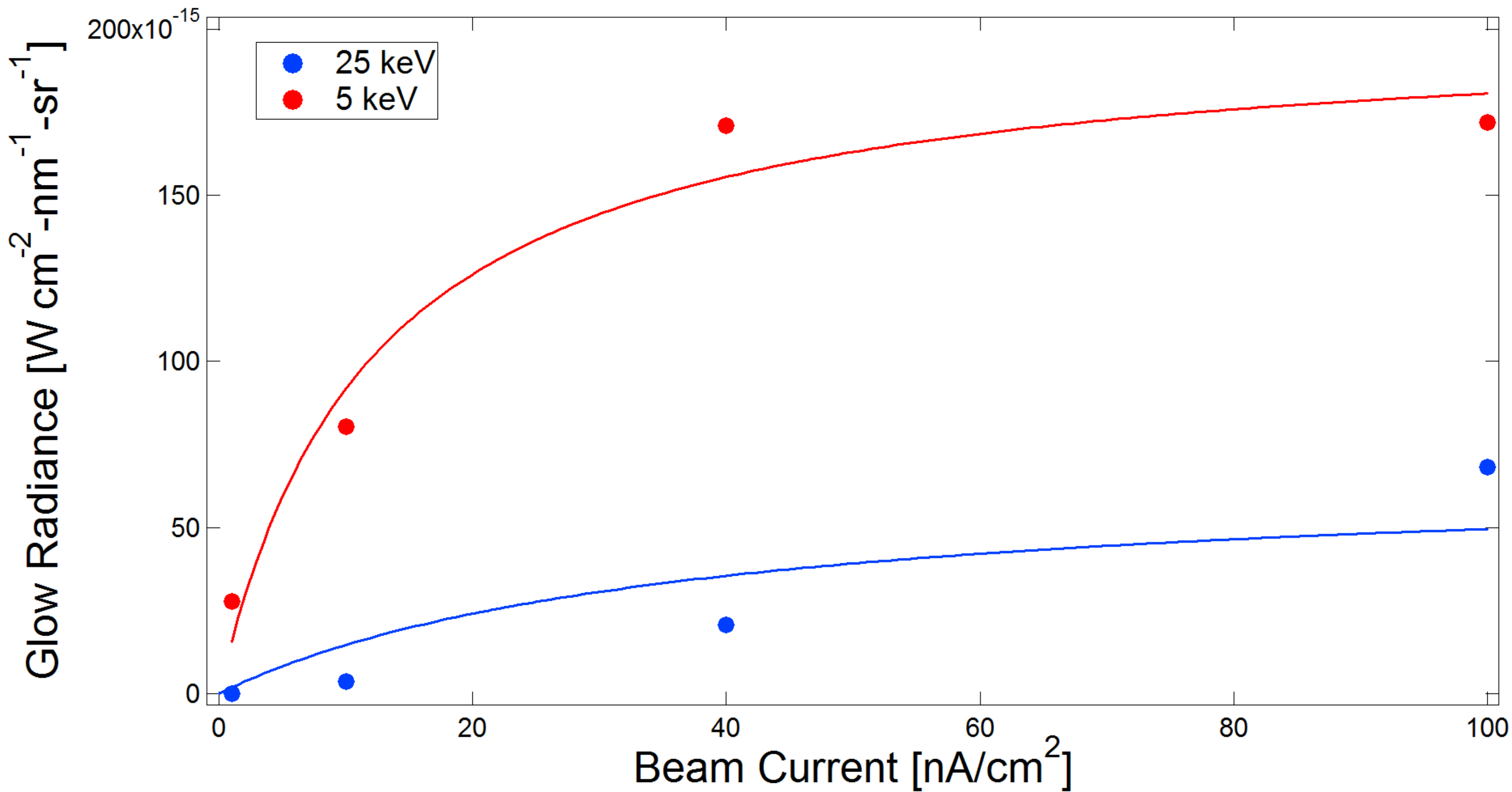
q_e: is the electron charge

ρ_m: is the mass density of the coating

Results

Incident Beam Current

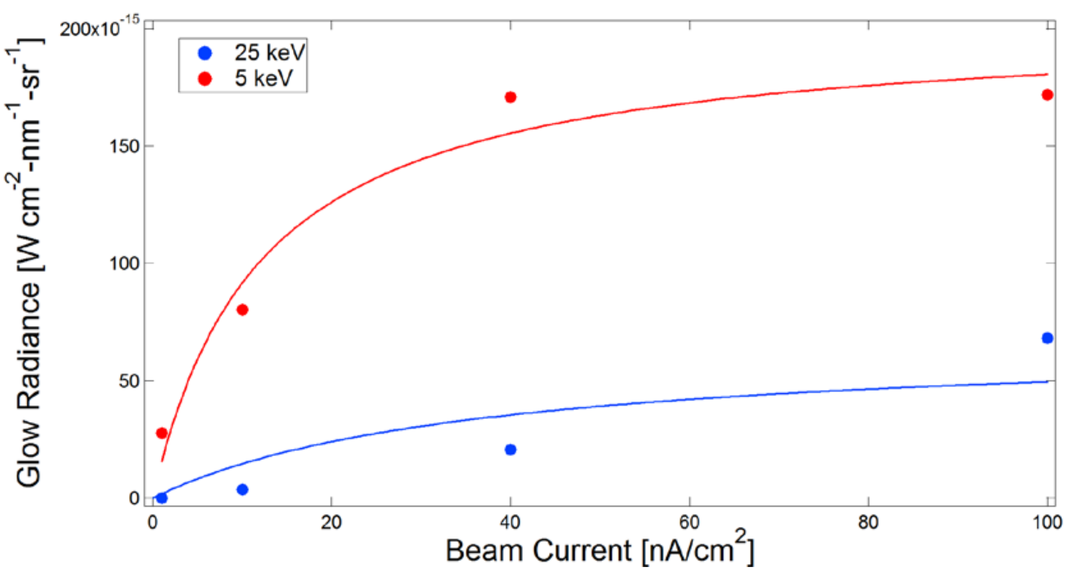
$$\dot{D}(J_b, E_b) = \frac{E_b J_b [1-\eta(E_b)]}{q_e \rho_m} \times \begin{cases} [1/L] & ; R(E_b) < L \\ [1/R(E_b)] & ; R(E_b) > L \end{cases}$$



Results

Incident Beam Current

$$\dot{D}(J_b, E_b) = \frac{E_b J_b [1-\eta(E_b)]}{q_e \rho_m} \times \begin{cases} [1/L] & ; R(E_b) < L \\ [1/R(E_b)] & ; R(E_b) > L \end{cases}$$



Low Currents: intensity is proportional to the incident current through the dose rate

High Current: saturation can occur when trap states fill, limiting the number of states electrons can decay into, and leading to

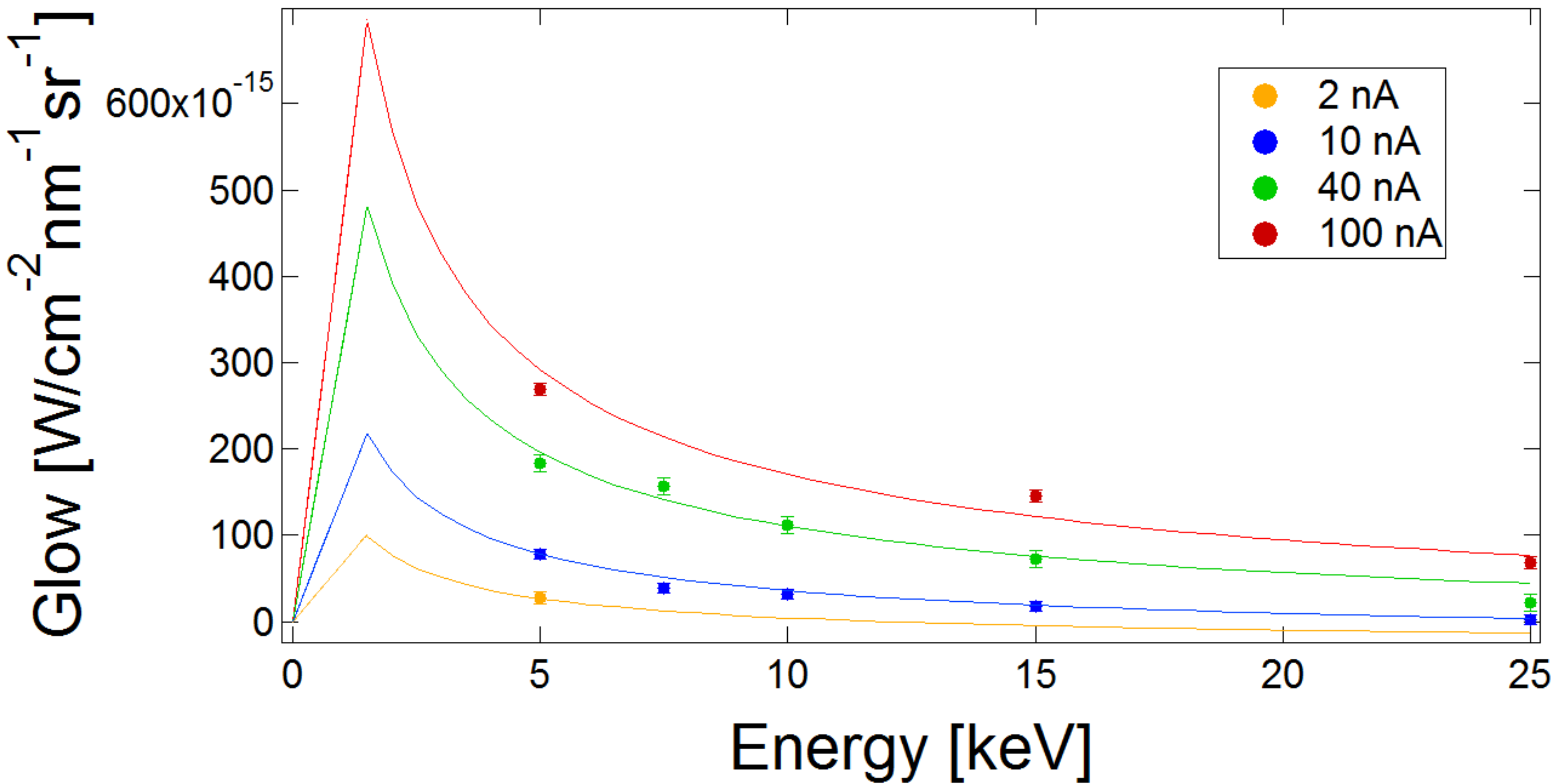
$$I_\gamma \propto \left(\dot{D} + \dot{D}_{sat}\right)^{-1}$$

$\dot{D}_{sat}$ is a material dependant saturation dose rate, found equal to ~10 Gy/s for these disordered SiO_2 coatings.

Results

Incident Beam Energy

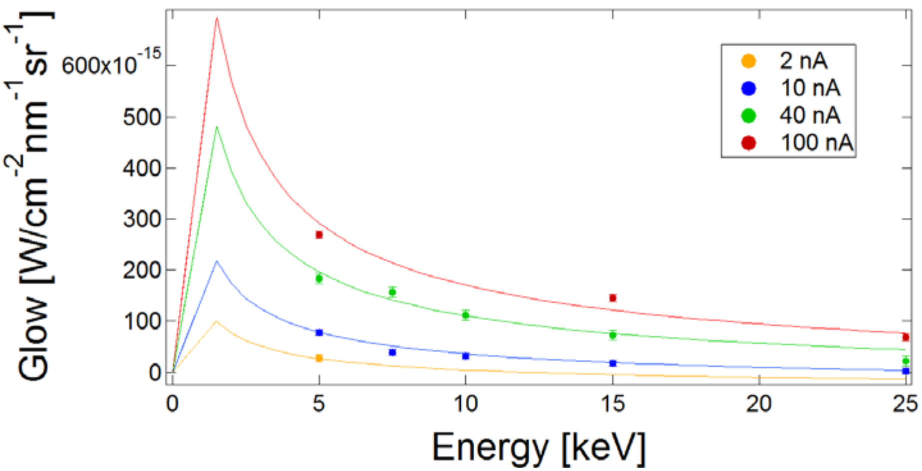
$$\dot{D}(J_b, E_b) = \frac{E_b\, J_b[1-\eta(E_b)]}{q_e \rho_m} \times \begin{cases} [1/L] & ; R(E_b) < L \\ [1/R(E_b)] & ; R(E_b) > L \end{cases}$$



Results

Incident Beam Energy

$$\dot{D}(J_b,E_b) = \frac{E_b\, J_b[1-\eta(E_b)]}{q_e \rho_m} \times \begin{cases} [1/L] & ; R(E_b) < L \\ [1/R(E_b)] & ; R(E_b) > L \end{cases}$$



Nonpenetrating Radiation {$R(E_{inc}) < L$}*:* all incident power is absorbed in the coating and intensity and dose rate are linearly proportional to the incident power density

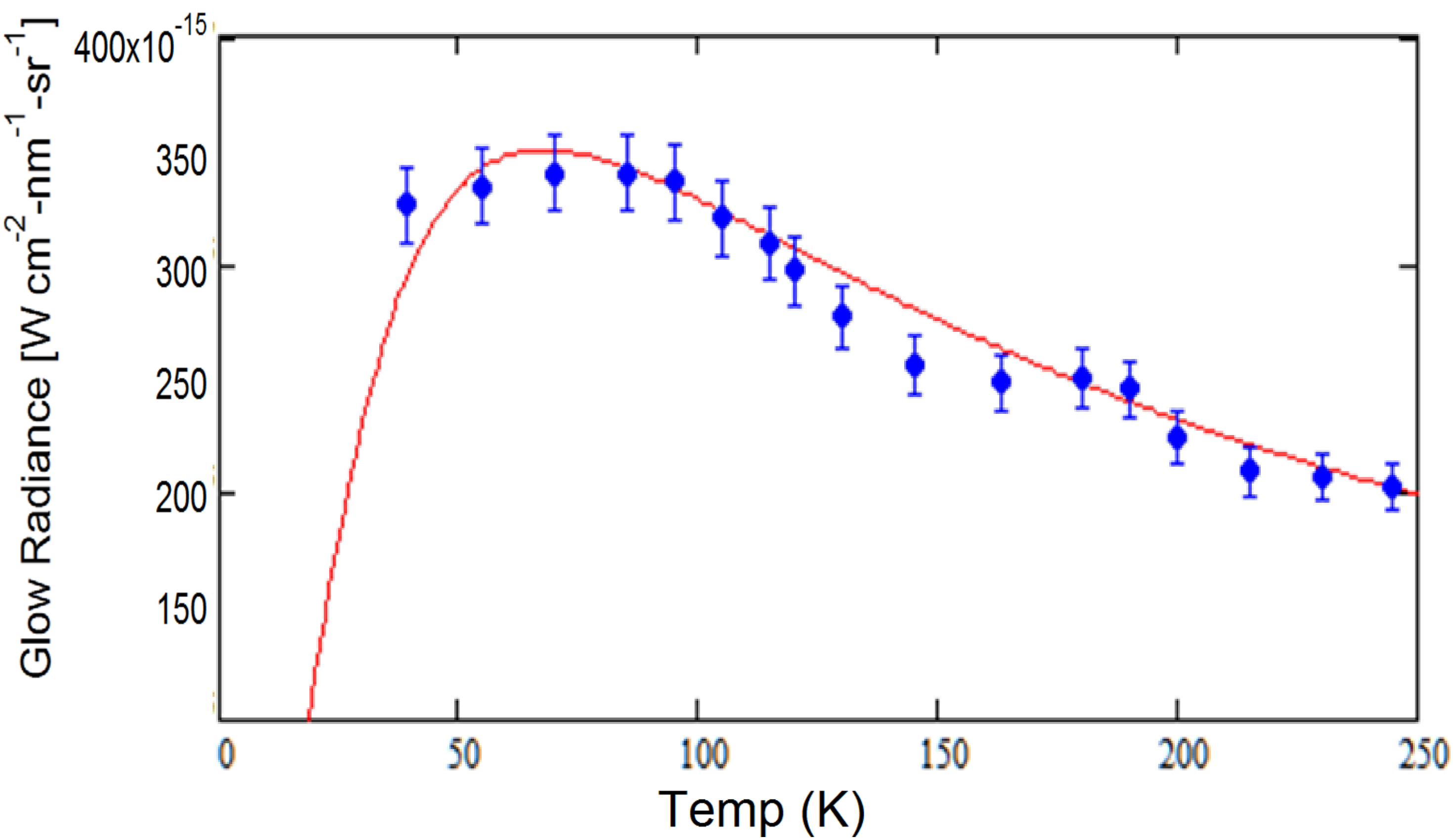
Penetrating Radiation {$R(E_{inc}) > L$}: the absorbed power is reduced by a factor of $L/R(E_{inc})$.

An energy-dependent correction to the incident flux is included in the dose rate equation to account for quasi-elastic backscattered electrons that do not deposit substantial energy; η is the backscattered electron yield. For the most part, this correction is small and weakly dependant on energy.

Results

Temperature

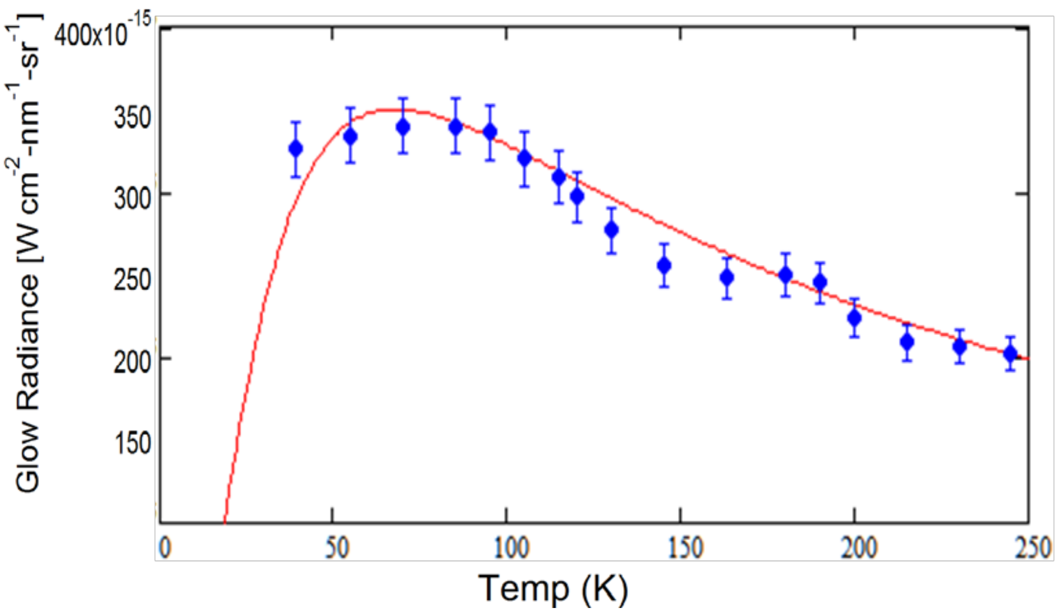
$$I_\gamma(J_b, E_b, T, \lambda) \propto \frac{\dot{D}(J_b, E_b)}{\dot{D} + \dot{D}_{sat}} \{[e^{-(\varepsilon_{ST}/k_B T)}][1 - e^{-(\varepsilon_{ST}/k_B T)}]\}\{[1 - \mathbb{A}_f(\lambda)][1 + \mathbb{R}_m(\lambda)]\}$$



Results

Temperature

$$I_\gamma(J_b, E_b, T, \lambda) \propto \frac{\dot{D}(J_b, E_b)}{\dot{D}+\dot{D}_{sat}}\{[e^{-(\varepsilon_{ST}/k_B T)}][1 - e^{-(\varepsilon_{ST}/k_B T)}]\}\{[1 - \mathbb{A}_f(\lambda)][1 + \mathbb{R}_m(\lambda)]\}$$



At higher temperatures, the thermal energy exceeds the mean energy depth of the shallow traps below the conduction band and $I_\gamma \propto \left(\varepsilon_{ST_Q}/k_B T\right)$

The thermal dependence of luminescence is proportional to

1. the number of electrons in the conduction band that can fall into the shallow traps

$$\propto \left[e^{-(\varepsilon_{ST}/k_B T)}\right]$$

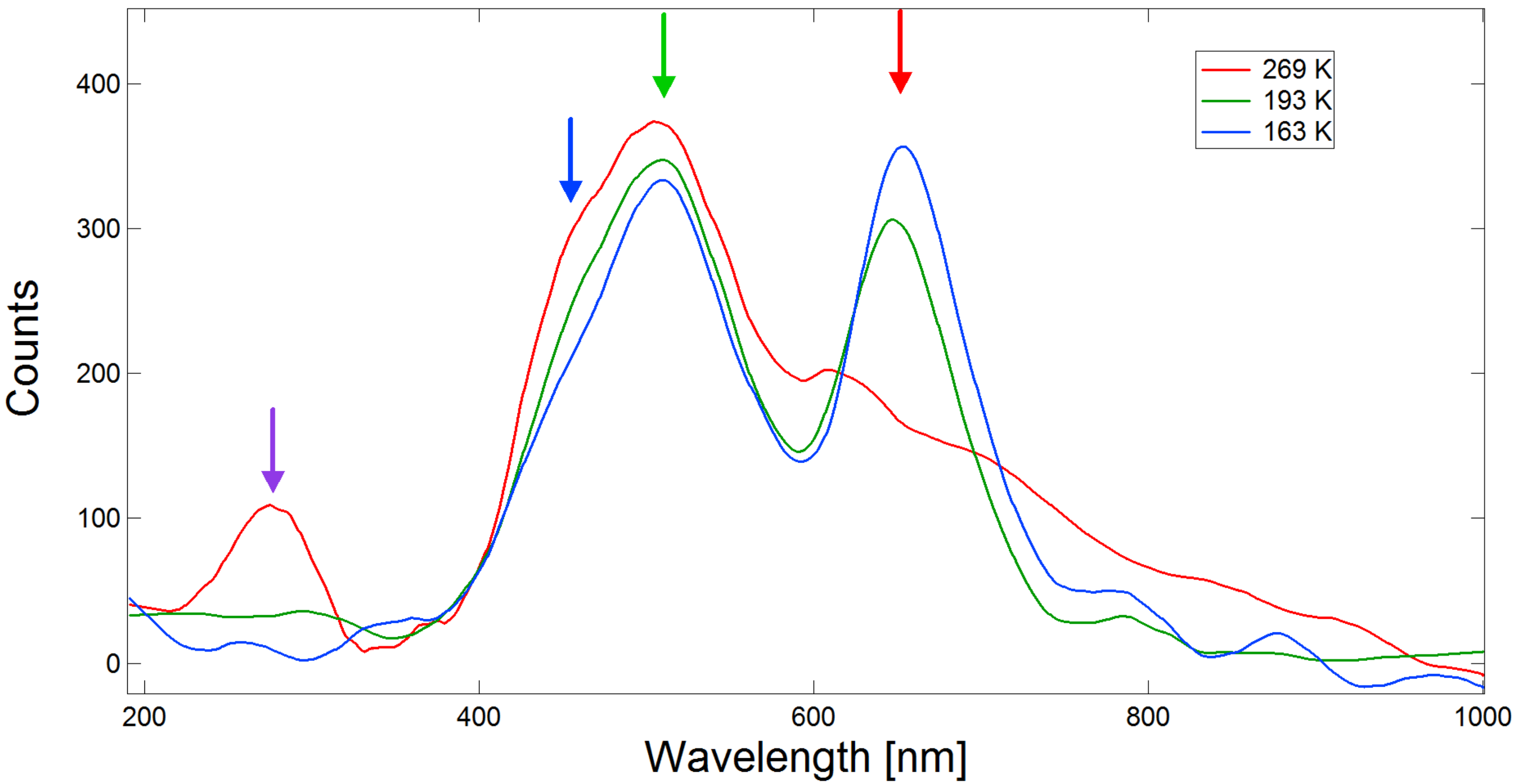
2. the fraction of electrons that are retained in the shallow traps and not thermally excited into the conduction band

$$\propto \left[1 - e^{-(\varepsilon_{ST}/k_B T)}\right]$$

Results

Photon Wavelength

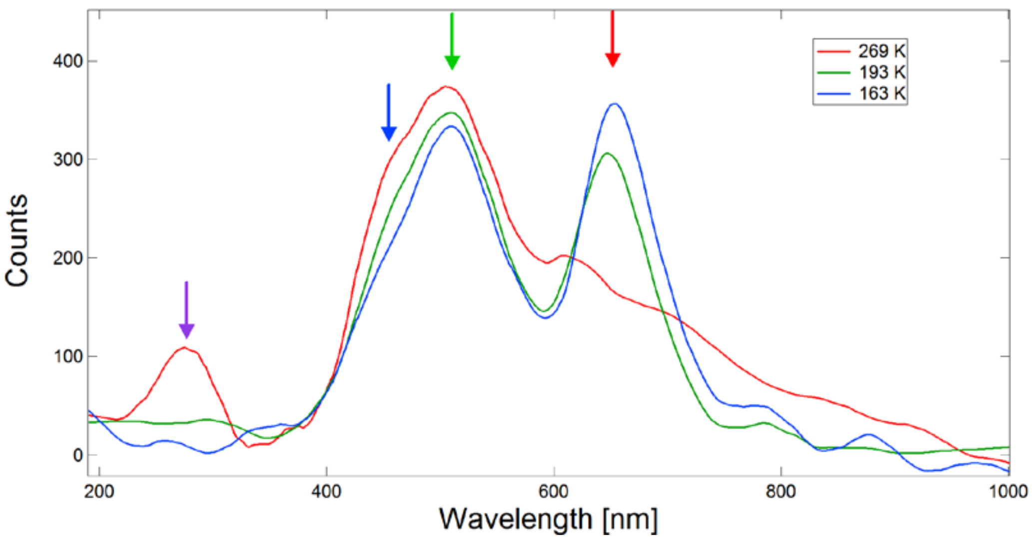
$$I_\gamma(J_b, E_b, T, \lambda) \propto \frac{\dot{D}(J_b, E_b)}{\dot{D}+\dot{D}_{sat}} \{[e^{-(\varepsilon_{ST}/k_B T)}][1 - e^{-(\varepsilon_{ST}/k_B T)}]\}\{[1 - \mathbb{A}_f(\lambda)][1 + \mathbb{R}_m(\lambda)]\}$$



Results

Photon Wavelength

$$I_\gamma(J_b, E_b, T, \lambda) \propto \frac{\dot{D}(J_b,E_b)}{\dot{D}+\dot{D}_{sat}}\left\{\left[e^{-(\varepsilon_{ST}/k_BT)}\right]\left[1-e^{-(\varepsilon_{ST}/k_BT)}\right]\right\}\left\{\left[1-\mathbb{A}_f(\lambda)\right]\left[1+\mathbb{R}_m(\lambda)\right]\right\}$$



Here, we account for photon propagation through the coating.

High Optical Absorption Coating: intensity is limited to emission from the near-surface region from which photons can escape and is approximately independent of electron energy.

Low Optical Reflection Metallic Layer: photons reflected from the metallic layer do not substantially increase the luminescence.

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Considerations

Detection of extremely faint signals (distant objects) observed by space-based observatories can be limited by background light levels from:

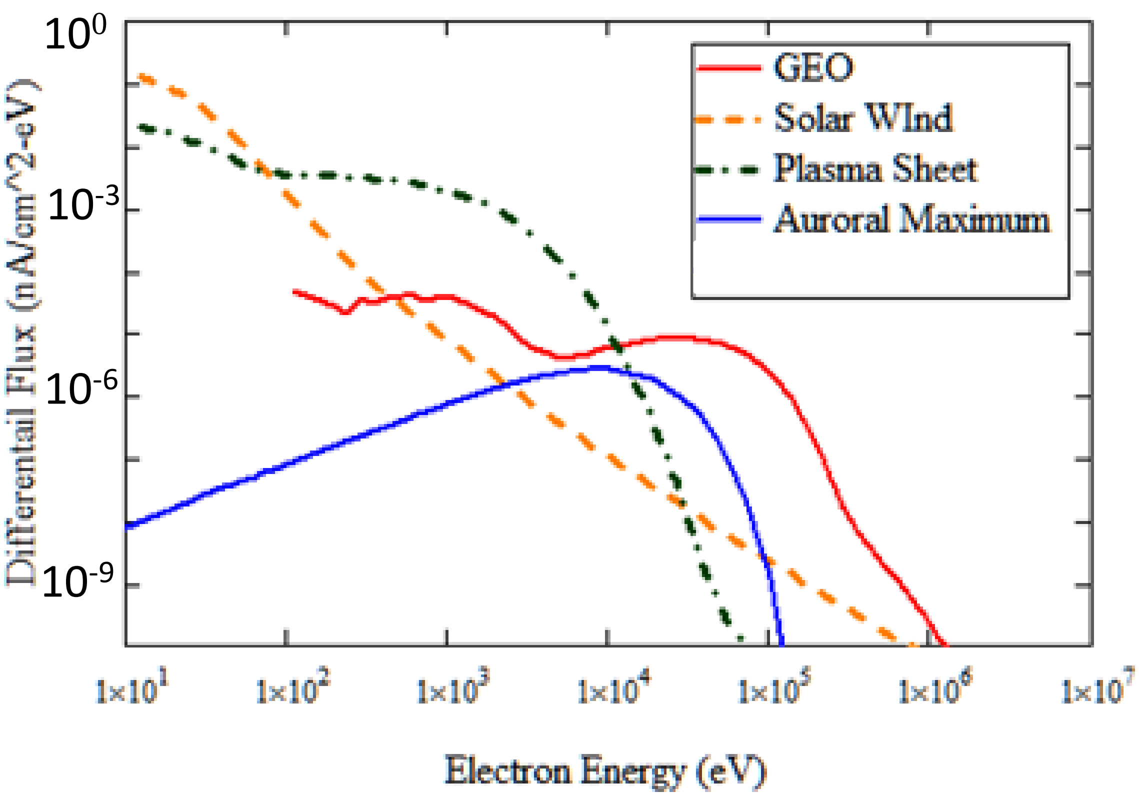
- astronomical sources within and outside our solar system (zodiacal and galactic background, respectively)
- contributions from the observatory itself (*i.e.*, thermal self emission in the infrared)
- scattered light from the combination of astronomical sources and observatory properties
- cathodoluminescence from electron impact onto coatings or optical components

A maximum stray light condition is often set by the zodiacal sky background. As a reference point, the intensity of the zodiacal background at 1AU near the south ecliptic pole is $8 \cdot 10^{-14}$ W cm^{-2} nm^{-1} sr^{-1} at 500 nm, $3 \cdot 10^{-14}$ W cm^{-2} nm^{-1} sr^{-1} at 1000 nm, and $6 \cdot 10^{-15}$ W cm^{-2} nm^{-1} sr^{-1} at 2000 nm.

To determine the magnitude of cathodoluminescence for a specific space-based observatory situation, to compare with these background sources, requires knowledge of:

Considerations

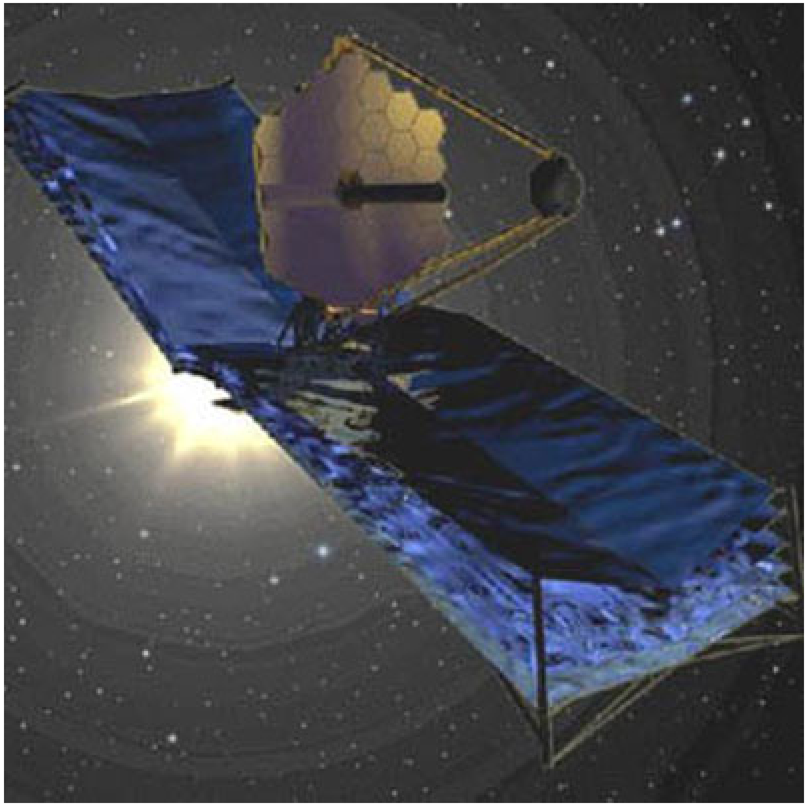
- The observatory electron environment and specifically the electron flux spectrum



These are typical flux ranges but fluxes for each observatory will depend on the particular environments that are encountered throughout the mission.

Considerations

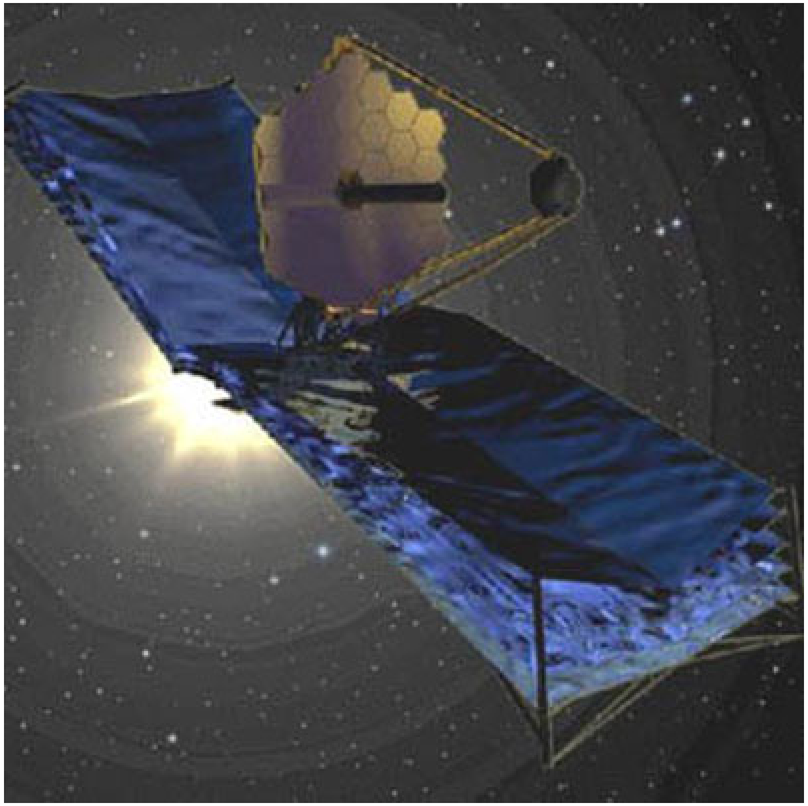
- The degree of baffling or shielding of electrons onto potentially luminescent optics



An open architecture and minimal shielding, often required for large observatories due to size and mass constraints, permits stray light to enter the optical path of the telescope and also exposes optical elements and surrounding support structures to greater environmental electron fluxes.

Considerations

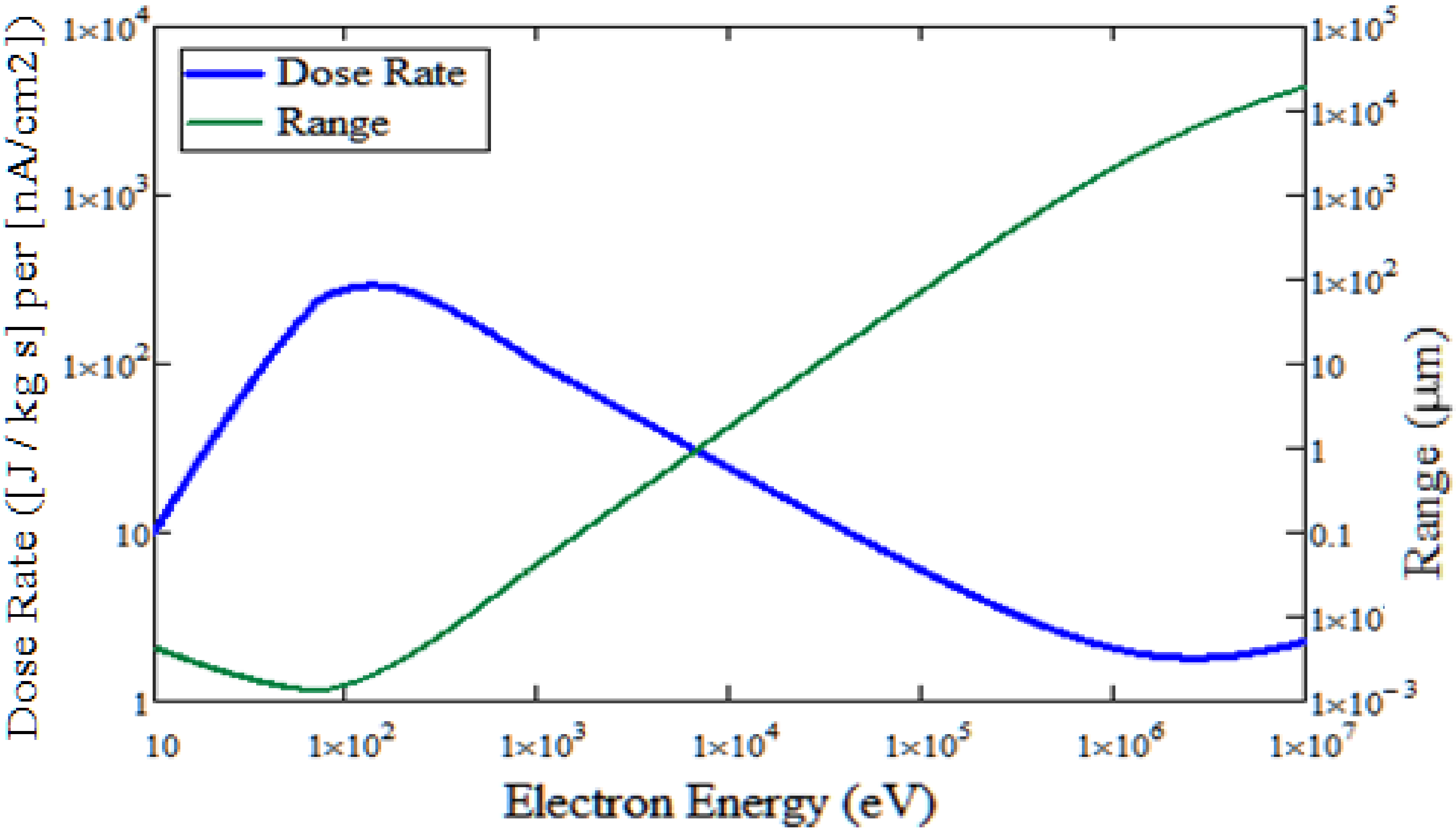
- The effectiveness of the optical system in transmitting the generated cathodoluminescence from the impacted optics to instrument focal planes



This depends on the juxtaposition of the luminescent elements and the location of stops along the optical path.

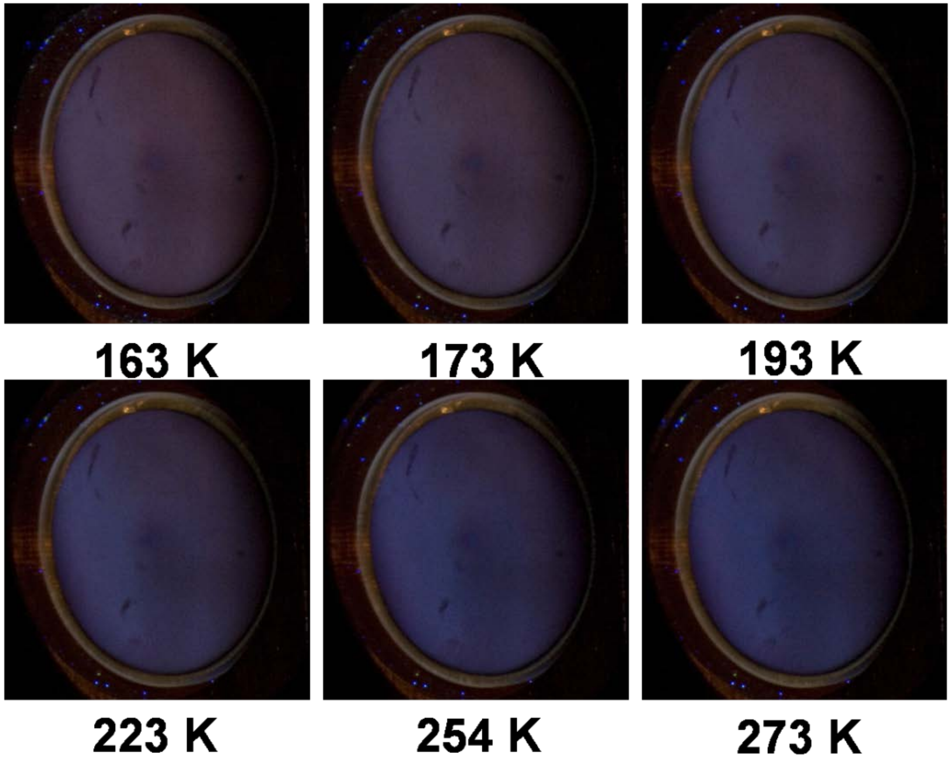
Considerations

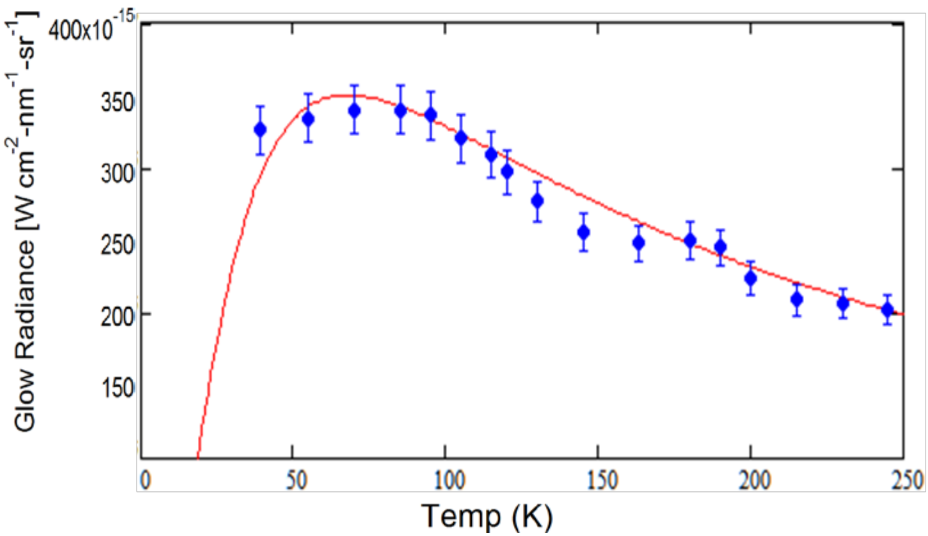
- The thickness of the luminescent coating



Considerations

- The temperature of the luminescent coating





Considerations

- The composition of the luminescent coating

To a modest extent, the luminescent spectrum and overall intensity will change with the exact composition and atomic scale structure of the luminescent coating.

See Dennison, JR: *Diverse electron-induced optical emissions from space observatory materials at low temperatures*

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Conclusions

- Disordered, thin film SiO_2/SiO_x coatings, commonly used as protective mirror coatings, exhibit cathodoluminescence under electron-beam bombardment.
- This was measured as a function of electron energy, beam current and temperature.
- A simple model was proposed that describes the dependence of this cathodoluminescence on irradiation time, incident flux and energy, sample thickness, and temperature.
- Other factors necessary for the estimation of the magnitude and effect of this potential source of background light for a particular mission include the electron environment and variability, considerations of baffling of the impacted elements, transmission of this luminescent light to instrument focal planes, thickness of the coatings used on particular elements, and the temperatures of the coated elements.
- The information provided in this study, coupled with these specific mission specifications, is sufficient to determine the risks posed to the performance of spaced-based observatories from space plasma environmentally-induced cathodoluminescence.

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