AN ASSESSMENT OF THE IMPACT OF SPACECRAFT GLOW ON THE HUBBLE SPACE TELESCOPE

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Summary of Existing Observations and Theory

Visible spacecraft glow was first observed on the Atmospheric Explorer spacecraft by Torr [1983] and studied in some detail with the Visible Airglow Experiment (VAE) on the AE-E spacecraft by Yee and Abreu [1983]. The AE-E was a spin-stabilized spacecraft without thrusters at an altitude of 140-280 km. The VAE contained six visible-wavelength photometers that measured a glow spectrum which: a. rose steeply in the red, b. decreased with a $\cos^3 \phi$ dependence from pointing into the ram direction of the spacecraft orbital motion, and c. decreased in intensity with increasing altitude with the same dependence as the measured atomic oxygen number atmospheric density [O] and not with the measured molecular nitrogen density [N_2]. Yee and Abreu [1983] proposed that the glow is produced by chemical reactions on the spacecraft surface as it sweeps through the atmospheric O, with roughly 5-8 eV per O atom available for excitation from the orbital motion of the spacecraft. This glow may in principal be produced by any of a number of species, including molecular band emission from OH, NO, and NO_2 (see Figure 1). The physical picture for the estimation of the surface brightness of the glow emanating above a surface is therefore:

column photon production = [O] x (orbital speed) x (efficiency)

where: [O] at 590 km = 4×10^5 cm^{-3} (solar min average)
[O] at 590 km = 3×10^7 cm^{-3} (solar max average)

and the efficiency for optical photon production (4000-8000Å) is 10^{-5} to 10^{-6} (measured on STS-3 and AE-E).

It has been proposed by Slanger [1983] and by Langhoff et al. [1983] that the observed glow on AE-E is from the excitation of the OH Meinel band system, which may be capable of producing all of the observed glow above 160 km altitude. This identification is supported by the detection of two spectral lines of the OH system with the Fabry-Perot spectrometer on the Dynamics Explorer [Abreu et al., 1983]. The existence of OH band emission would imply that there exists a much brighter near-IR glow than observed to date in the visible (see Figure 2), and thus poses a risk for the development of second-generation IR SI's for Space Telescope.

Observations on the shuttle indicate that there are several different "glows" operating, and the functional dependencies governing the brightness of these different glows are not well understood. The situation is complicated by the existence of thruster firings on the shuttle, as well as the generally larger size of the spacecraft and resulting greater residual atmosphere and induced plasma and spacecraft charging. The early pictures of the shuttle tail and aft bulkhead taken on STS-3,-4,-5, and -9 revealed a glow which varied in brightness with the surface material, varied with the timing with respect to the thruster firings, showed a $\cos^{1/2}\phi$ dependence in brightness with pointing away from the orbital ram direction, and exhibited a spectrum similar to that observed on AE-E. Ground-based imaging of STS-9 at wavelengths of 1.6 and 2 microns detected the shuttle (as a whole) only at 2 microns, as would be expected from OH band emission, but the intensity of the emission was uncertain due to tracking difficulties [Witteborn et al., 1985]. A hand-held movie camera operated by Owen Garriott revealed a dramatic brightening of the shuttle tail and aft bulkheads following the firings of the vernier thrusters. This emission appeared a few seconds after the thrusters fired and decayed a few seconds later. However, the surface glow has been observed on the shuttle even when the thrusters were not firing (STS-3). Two far-UV cameras flown on Spacelab 1 (FAUST and WFC) both showed considerable fogging of their film, which may have been due to any of a combination of atmospheric twilight emissions, tropical arc OI 1304 and 1356 Å emissions, or an additional far-UV glow on the Shuttle.

Moderate resolution (3-6 Å) spectroscopy was performed on the STS-9 mission with the Imaging Spectrometric Observatory (ISO) from 1150-8000 Å [Torr and Torr, 1985]. Specific observations for glow were performed in a dedicated pointing into the ram direction and tangent to the Earth at an altitude of 250 km, although the instrument did not view any direct surfaces. The ISO spectrometers were capable of detecting line and/or band emission but not continuum glow due to uncertain detector background caused by rapid temperature changes. The detected UV and visible spectra are shown in Figures 3 and 4. The emissions shown in these spectra are a combination of atmospheric and potential glow emissions: more detailed analysis of these data will be required to identify which of the observed features may be due to glow. The visible band emission observed from 4000-8000 Å has a spectral slope consistent with that observed on AE-E, but the brightness of the visible glow reported at 250 km is similar to that observed by AE-E at 140-145 km. These band spectra suggest a contribution from the N_2 first positive system, and at different times the brightness of the emission at all wavelengths was observed to vary by at least an order of magnitude.

Theoretical studies of the glow have been performed to study the physical processes responsible for the glow. Yee and Dalgarno [1983] have determined the lifetime(s) of the glowing species (0.3 ms) from the spatial decay of the emission above the shuttle surface [Banks et al., 1983]. They conclude that OH band emission is unlikely to explain all of the observed shuttle glow, but may still radiate strongly in the IR. Swenson et al. [1985] propose NO_2 recombination continuum as the dominant source of radiation based on energetic arguments and the apparent lack of band structure in the glow at 30 Å resolution from 4000-8000 Å. There are no near-IR observations available to test either of these hypotheses. Torr and Torr [1985] identify N_2 first positive band emission from their STS-9 spectra. There is additionally a plasma theory for the glow, in which a surface plasma layer heated by non-linear plasma-wave interactions provides the glow excitation. The required plasma density is known to exist near the shuttle, but only under sunlit conditions, and the AE-E glow data showed no dependence on daytime/nighttime electron density variations [Yee et al., 1985]. The plasma theory also predicts blue/UV enhanced glow emission, which has never been observed.

Scaling Observed Glows to Space Telescope

Accurately scaling the observed glows to Space Telescope requires much better information about the physical processes producing the glow and the functional dependencies of the glow brightness than is currently available. Many different species have been proposed as glow emitters (OH, NO_2, NO, N_2), making the spectral character of the glow uncertain. The glow brightness is believed to depend on atmospheric density, which varies quite strongly with solar activity at a given altitude (see Figure 5). Other functional dependencies to be determined are:

- the quantitative effect of thruster firings (not an issue for ST other than to interpret shuttle glow observations)
- changes in the glow spectrum during thruster firings
- dependence of glow on spacecraft size
- dependence of glow on spacecraft materials and cleanliness
- dependence of glow on angle to the orbital ram direction
- existence of extended glow above spacecraft surfaces

It must be concluded that the extrapolation to ST will be very uncertain until these factors are better understood. For example, the difference in scaling the observed glow brightnesses from AE-E and the ISO to ST altitudes by [O] is shown in Figure 6.

The actual contamination by glow in the focal plane of the Space Telescope depends not only on the surface brightness of the glow above a particular surface but also on the extent of the glow above each surface and how well the emission is baffled and thus prevented from reaching the focal plane. As long as the glow is confined to 10-20 cm above any given surface, the ST is a very well-baffled telescope and relatively little of that flux will penetrate to the focal plane. If any glow extends into the OTA field-of-view of the sky, however, the presumably isotropically emitting glow will be competing directly with the sky background to contaminate ST data. Perkin-Elmer has performed an analysis of the contribution to the total focal plane flux made by surface-localized glow using the following assumptions:

- $[O] = 3 \times 10^{7}\ cm^{-3}$ (average solar max conditions)
- photon production efficiency $1\text{-}3 \times 10^{-5}$
- glow extends 20 cm above the surface

These efficiencies were roughly measured for the ST materials (Chemglaze Z306 and anodized aluminum) on previous shuttle flights, but no information is available on the glow of Al+MgF_2. The predicted focal plane fluxes are plotted in Figure 7 as a function of angle to the ram direction. The case within 15° of upwind is uncertain since we do not know how the primary mirror will glow under direct exposure to the ambient atmospheric ram, but this will hopefully never be put to the test in flight. At all other angles the focal plane glow flux is predicted to be safely below the average sky background level of roughly 23 mag/arc sec^2.

The tolerable levels of extended glow emission (where "tolerable" is defined as less than or equal to the sky background) are plotted in Figure 8 as a function of wavelength in the aeronomer's units of Rayleighs/Å. Comparison with Figure 6 shows that even direct viewing glow emission should not be a problem due to the decreased [O] at 590 km. If the glow is somewhat extended and brightens in the near-IR (neither of which would be a particular surprise), however, the glow may be the limiting factor on ST sensitivity in the near-IR spectral range. An additional illustration of the relation between glow brightness and ST detection limits is shown in Figure 9 as a plot of the sky brightness equivalent to the flux in one planetary camera (PC) pixel that would be received from the representative blue spectrum of a hot star or QSO of $m_v = 30$, which is in turn equal to the sky background per PC pixel at 5500 Å.

Work Needed to Address Immediate Concerns for Space Telescope

The information required for Space Telescope can be divided into the near-IR, visible, and UV spectral ranges. Although a better understanding of the glow phenomenon is unlikely to influence any ST hardware at this stage of the program, the existence and characteristics of any unacceptably bright glow emissions will affect both ST operations and the planning for second-generation SI's. The ST project recommendations are therefore aimed at addressing the following problems before ST launch:

1. The existence and brightness of any near-IR glow.

The indication from the existing visible spectra is that the maximum glow brightness will be observed in the near-IR spectral range. The region from 8000 Å to 5 microns is of great interest in planning for second-generation SI's and has never been observed for glow! Spectroscopy at these wavelengths is also crucial to identifying the emitting species and excitation conditions, including knowing the lifetimes of the excited states which in turn determines the extent of the glow above a surface. It should also be noted that the different theories for molecular glow predict vastly different brightnesses in the near-IR.

2. Validate the brightness and altitude dependence of the visible glow.

Although the rough spectrum of the glow from 4000-8000 Å is known, the brightness of the glow above any given surface is uncertain by 1-2 orders of magnitude due to our lack of knowledge of the excitation processes. Other factors to be studied are listed in the conclusion of this section.

3. Does there exist a UV glow?

The visible spectra suggest that the brightness of the continuum glow is decreasing into the UV, and upper limits to any UV glow derived from earlier spaceborne airglow spectrometers indicate that there is no bright UV continuum glow. None of the earlier instruments looked at surfaces exposed to the ram, however, and it is conceivable that known atmospheric UV line and band emissions may be enhanced by the passage of spacecraft through the atmosphere. Candidate atmospheric emissions are OI 1304 Å and 1356 Å (which are known to be particularly bright in the tropical arcs at $\pm 15^\circ$ magnetic latitude), NO gamma and delta bands (1900-2400 Å), N_2 Lyman-Birge-Hopfield bands (roughly 1000-2000 Å), and various lines of NI and N_2.

For all spectral regions the functional dependencies need to be determined between glow brightness and:

- -atmospheric density and species
- -angle of pointing to the ram vector (including possible wake glow)
- -surface material and composition
- -spacecraft charging and outgassing
- -distance above the surface (lifetimes of excited states)
- -relation to thruster firings

References

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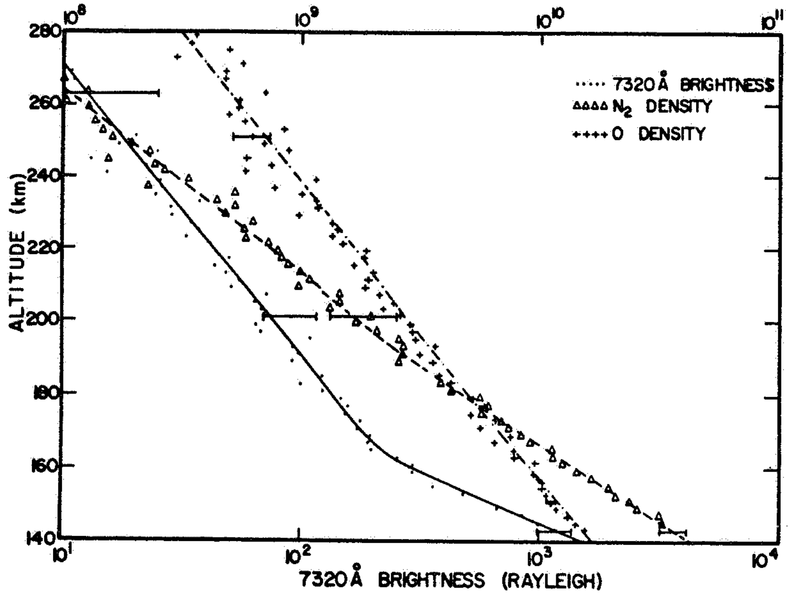

Fig. 1. The altitude variation of the glow emission at 7320 Å, along with the measured number densities of atomic oxygen and molecular nitrogen.

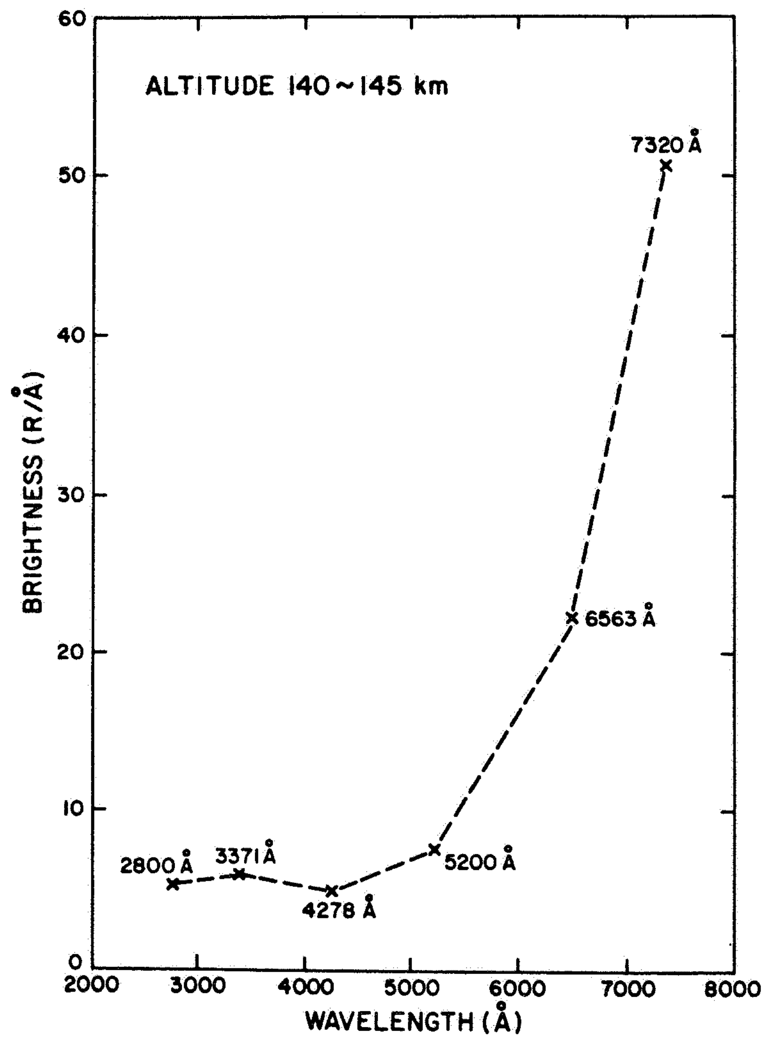

Fig. 3. The spectral variation of the glow emission at 140-145 km.

Fig. 1. Figures from Yee and Abreu [1983] showing AE glow properties.

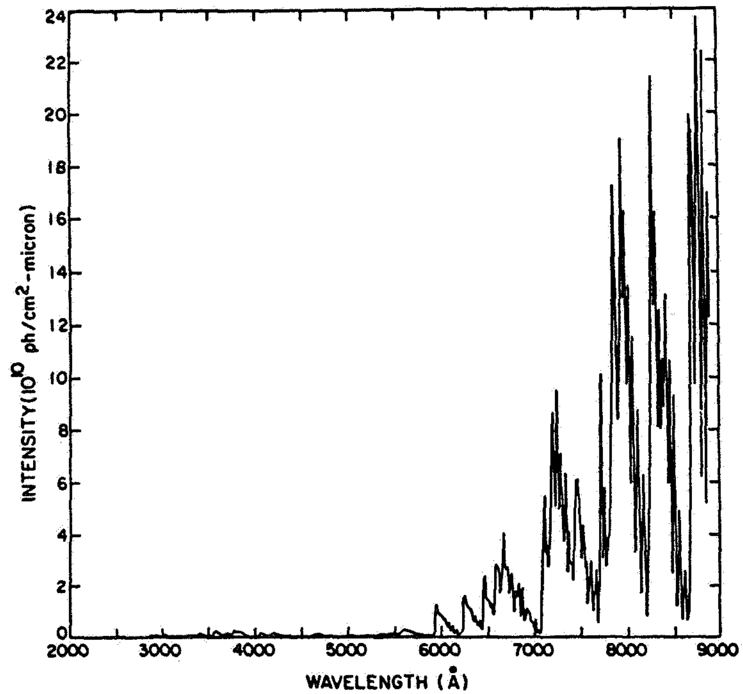

Fig. 1. The emission intensity of the OH Meinel system between 2000-7500 Å at 20 Å resolution. The spectrum is constructed for the case when all vibrational levels are equally populated and rotational distribution is thermal at 300 K. To give an absolute scale, we assume arbitrarily that there are 10^{10} particles cm^{-3} radiating in a layer 1 cm thick.

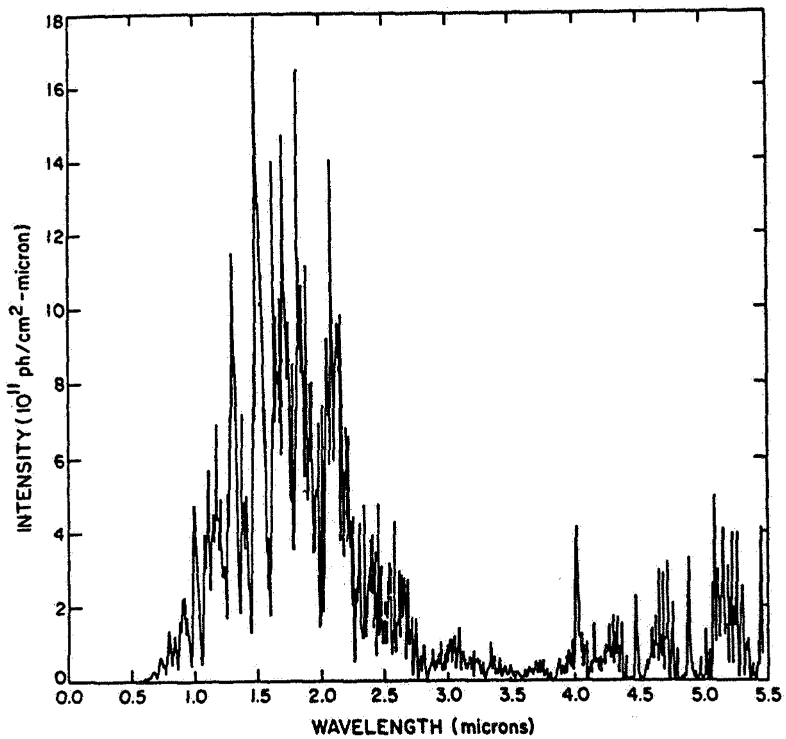

Fig. 2. Same as Figure 1 except that the spectrum is extended to 5.5μ and is at 100 Å resolution.

Fig. 2. Modeled OH band emission spectrum from Langhoff et al. [1983].

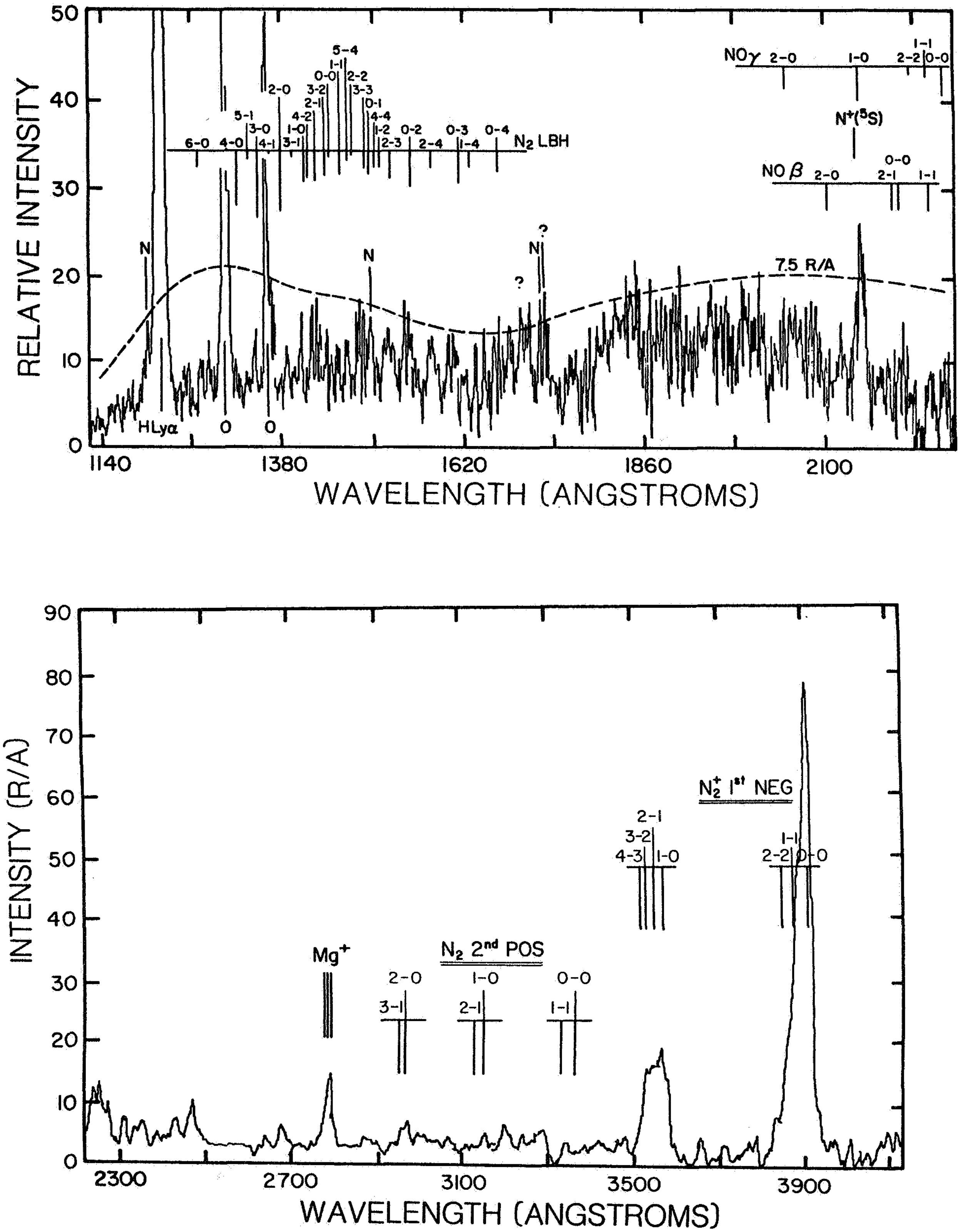

Fig. 3. Shuttle glow spectra from Spacelab 1 (from Torr and Torr [1985]).

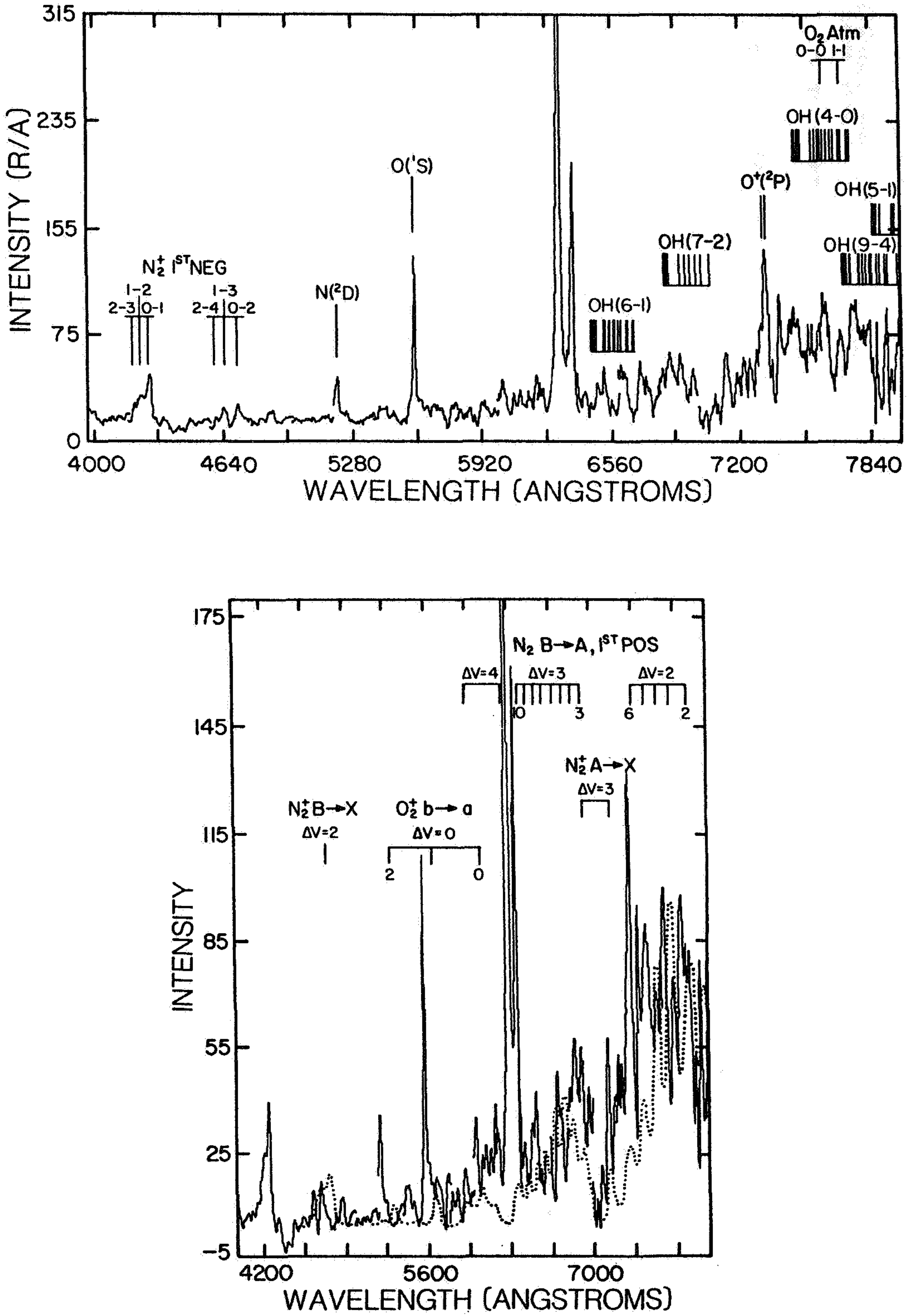

Fig. 4. Shuttle glow spectra from Spacelab 1 (from Torr and Torr [1985]).

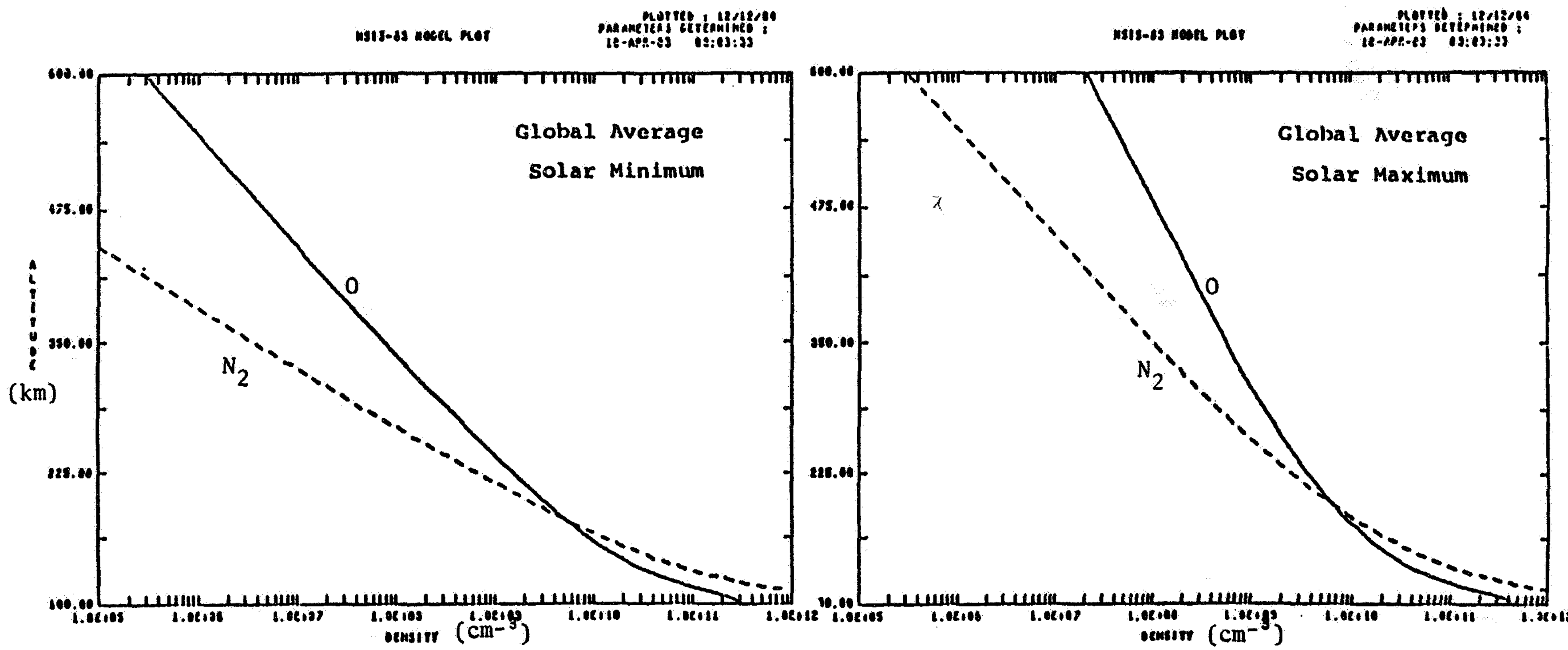

Fig. 5. MSIS model atmospheres from A. Hedin (GSFC).

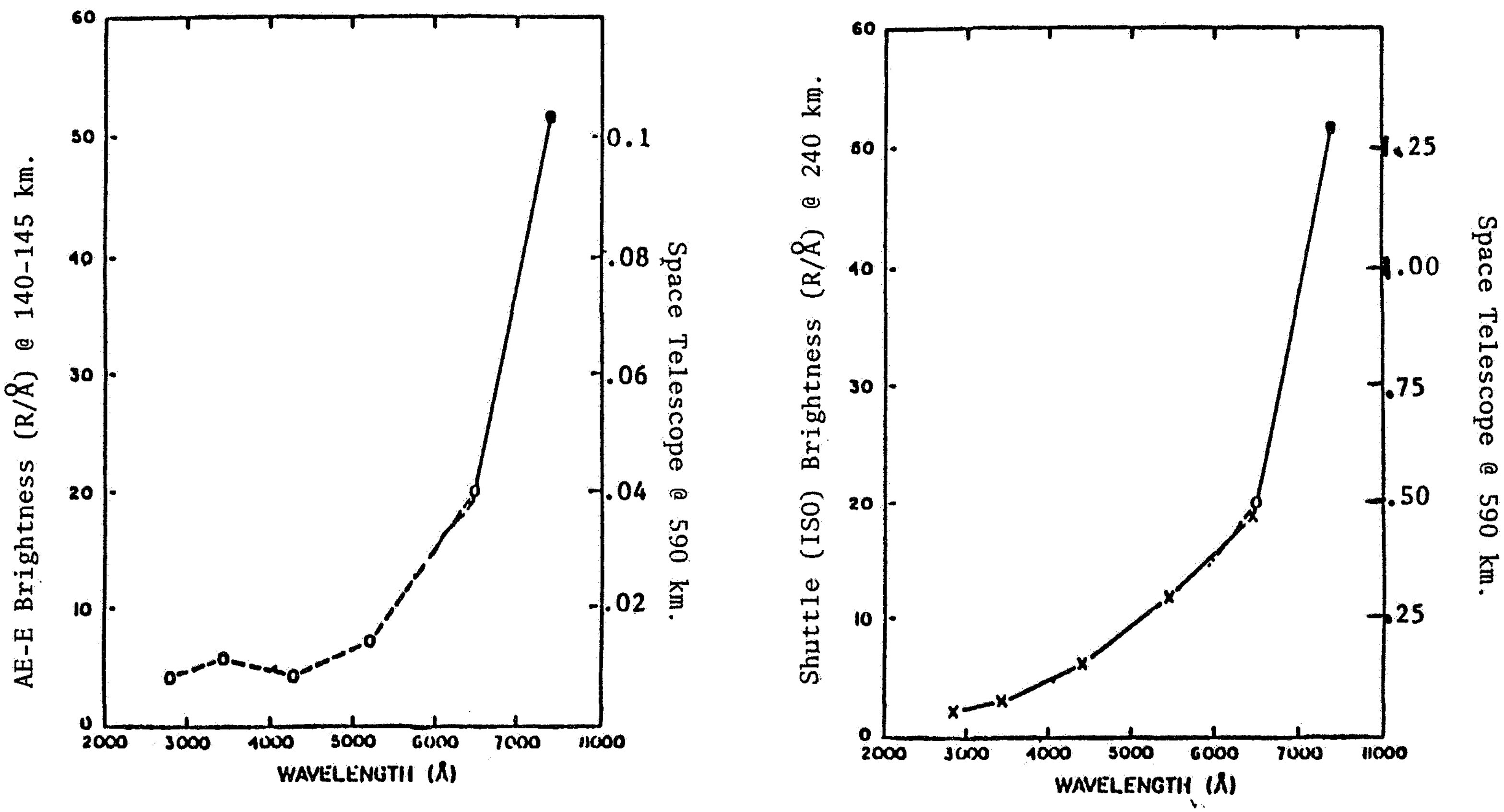

Fig. 6. Scaling observed glow brightnesses to ST altitudes (for solar max. [O] altitude profile).

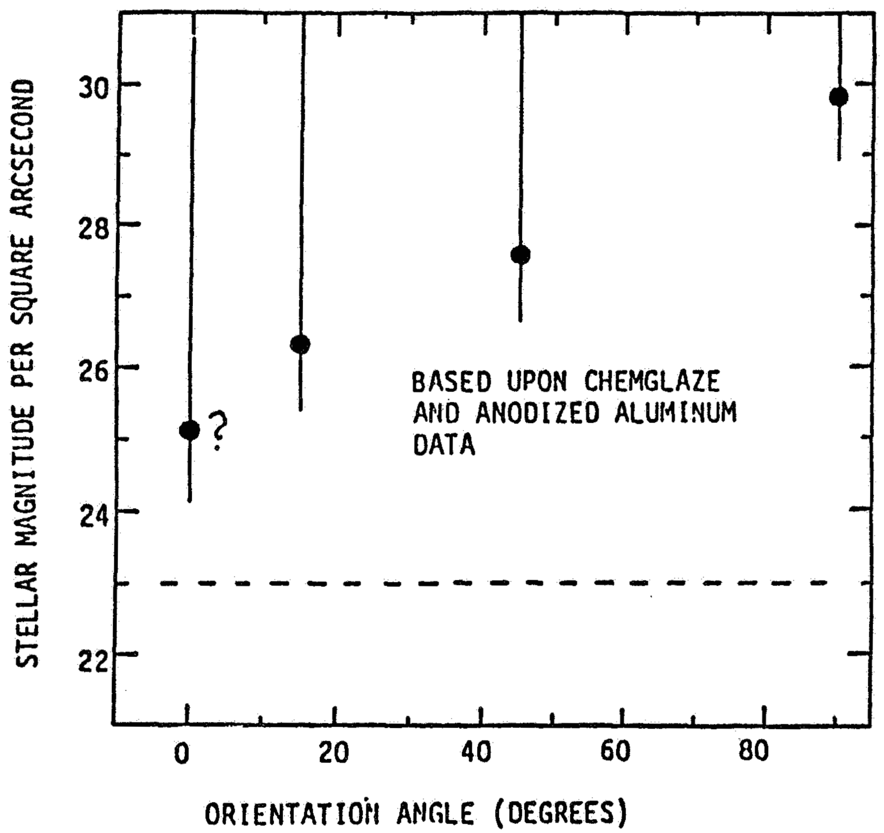

Fig. 7. Total glow induced focal plane straylight irradiance as a function of the angle between the telescope axis and incident oxygen vector. The zero degree case, being dominated by glow from the primary mirror, has the greatest uncertainty since glow from the MgF_2 coating has not yet been characterized.

1st Example: Plot the expected sky background due to zodiacal light in units of Rayleighs/Å

- Assume average zodiacal light brightness of 60 S_{10} units [Dube et al., 1977] at 5500 Å: 60 S_{10} = 0.26 Rayleighs/Å = 23.3 m_V/arc sec^2.
- Scale to other wavelengths by solar spectrum (observed to be accurate from 1800 Å to 3 microns)

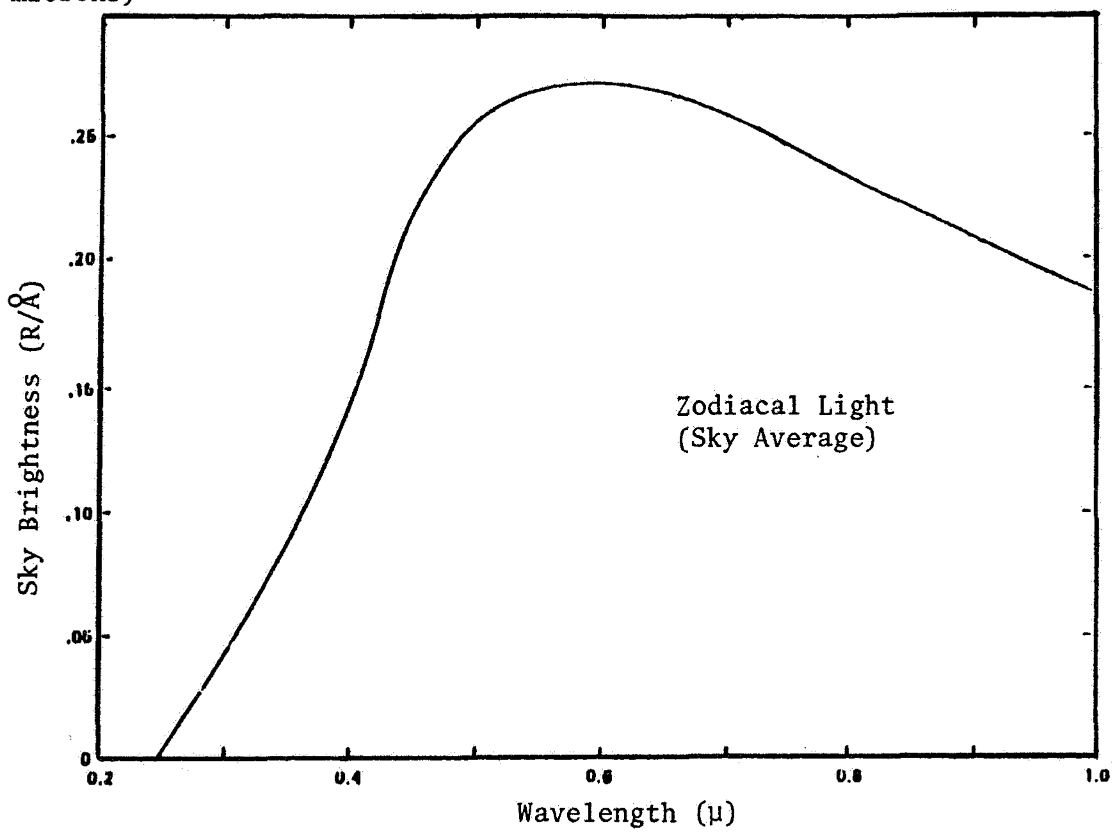

Fig. 8. Comparison of glow brightness with ST detection limits.

<u>2nd Example</u>: What sky brightness is equivalent to a point source with a flat spectrum (in F_ν units) filling one planetary camera pixel?

- Assume point source is equal to sky background of 23.3 mag/arc sec^2 scaled to 1 PC pixel of 0.048 x 0.048 arc sec^2.
- Equivalent source (QSO or hot star) has F_ν = 4 x 10^{-32} erg/cm^2-sec-Hz or m_v = 30.

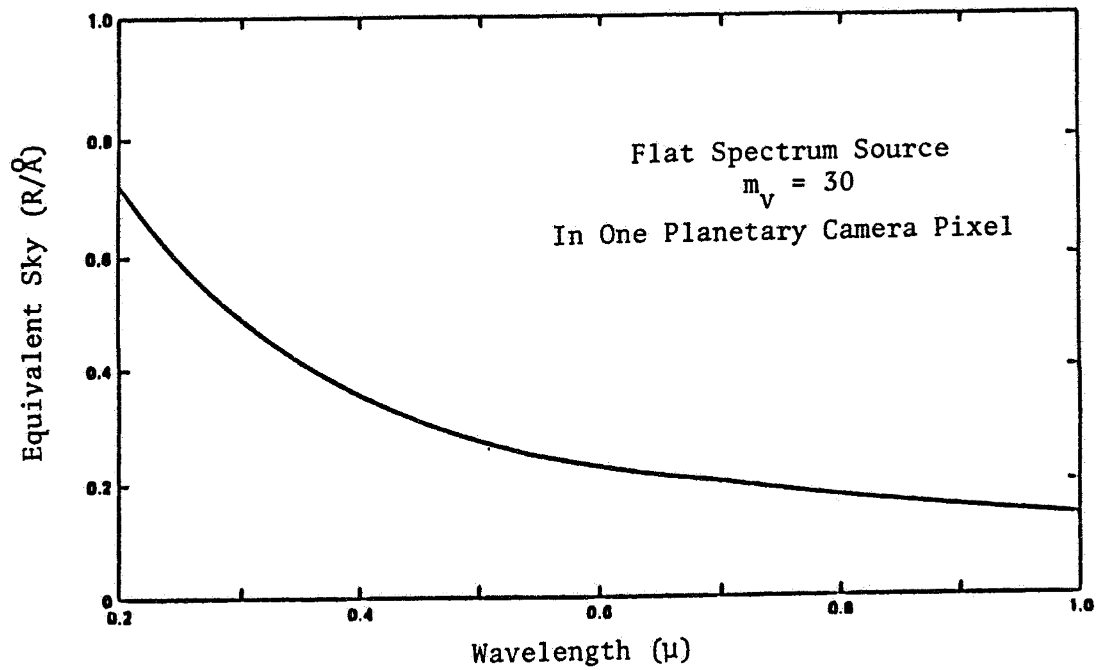

Fig. 9. Comparison of glow brightness with ST detection limits.