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DETECTION OF SURFACE GLOW RELATED TO
SPACECRAFT GLOW PHENOMENON

By

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DETECTION OF SURFACE GLOW RELATED TO
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ABSTRACT

We have developed a high flux source of low energy neutral beams to study the spacecraft glow phenomena by using a biased limiter to neutralize plasma in ACT-1. Beams of nitrogen and nitrogen-oxygen mixtures with energies of 1 to 15 eV and fluxes $> 10^{14}/\text{cm}^2/\text{s}$ were directed on target surfaces consisting of Z-302 and Z-306 paints. With the nitrogen beams we successfully detected a glow due to beam-surface interactions. In addition, we discovered a volume glow effect due to beam-gas interactions which may also play a role in spacecraft glow.

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I. INTRODUCTION

In orbit the Atmospheric Explorer Satellites and the Space Shuttle are observed to radiate over a region that usually extends to 20 cm, and in some places, perhaps to as much as a few meters from the surface. This spacecraft glow has an optical, infrared, and possibly an ultraviolet component. Detailed observational data are relatively sparse, consisting primarily of coarse spectral analysis of the glow, the glow intensity as a function of atmospheric constituent density, the sensitivity of the glow to surface materials, and the nature of the plasma environment [1-4].

The glow is thought to arise from aeronomic chemistry due to the collision of the spacecraft with the ambient atmosphere. The orbital speed, ~ 8 km/sec, corresponds to a relative kinetic energy of the gas particles with the ram side of the craft of ~ 4 eV to 10 eV. The conversion of this kinetic energy into the formation of molecules in excited states, followed by emission, is thought to be the source of the glow [1, 5-7].

Laboratory experiments to study this effect are lacking because the velocity and flux levels found in the spacecraft environment have not been duplicated on the ground for the appropriate species. Therefore, it is important to create a laboratory source of 3-10 eV neutral atoms and molecules (O , O_2 , N , N_2 , ...) with sufficient particle flux (10^{14} to $10^{15}/\text{cm}^2/\text{sec}$) to bombard surfaces under conditions similar to those near the spacecraft and to carry out spectroscopic analysis of the glow.

Here we report on our development of a ground-based experiment to study spacecraft glow phenomena. For this project we had two major goals: (1) to establish a facility for the production of low energy (1-15 eV) neutral beams of atomic and molecular nitrogen and oxygen with fluxes $\geq 10^{14}/\text{cm}^2/\text{s}$ illuminating an area $\sim 100 \text{ cm}^2$, and (2) to search for photon emission (glow)

from targets due to beam-surface interactions. We successfully achieved both these goals and, in the course of our experiments, we observed an additional light production mechanism of interest to spacecraft glow.

The experiments during this period were carried out using nitrogen and air plasmas at densities of a $(1-3) \times 10^{12} \text{ cm}^{-3}$ and targets coated with Z-306 and Z-302 paints (which are surface coatings used on spacecraft). We obtained emission spectra from the glow using photomultiplier tubes and bandpass interference filters (2000-8000 Å), and we used grating spectrographs to study plasma emission spectra for comparison to the glow.

Our key experimental results so far are (1) discovery of a surface glow on insertion of a target; (2) measurement of an exponential fall-off in surface glow intensity with distance from the target; (3) detection of a volume glow due to beam-gas particle interactions, and the study of this volume glow as a function of energy, pressure, target gas, and plasma source; and (4) using the intensity of this volume glow, an estimation of an achievable neutral beam flux of $(1-6) \times 10^{14} / \text{cm}^2 / \text{s}$ at the targets.

II. EXPERIMENT

A. New Method of Neutral Beam Production

The approach we have taken to produce a low energy neutral beam is different than traditional methods, such as charge exchange of positive ions or photodetachment of negative ions. Instead, we use an electrically biased metal plate (a limiter) to intercept, accelerate, and neutralize the ions from a plasma discharge. These neutrals reflect from the surface of the plate to produce a beam. The intensity of the beam is determined by the ion current to the limiter, whereas the energy of the beam can be controlled with the bias

voltage. Beam currents of the order of 1 amp at the limiter can be readily achieved in the Advanced Concepts Torus-1 (ACT-1) [8] device at PPPL.

Ions formed in ACT-1 are confined for about 2 msec and most of them are lost by drifting radially outward across field lines onto the wall. A fraction of these ions (up to $\sim 1/3$) strike the biased limiter and reflect as neutrals. A calculation using the TRIM code [9] predicts that a high percentage of the particles are reflected with nearly their full energy if the mass of the atoms making up the target (limiter) is much greater than that of the incoming particles. Furthermore, the code predicts that by positioning and orienting the limiter appropriately, a high percentage of the neutrals will be directed out of the machine where they can enter a drift tube containing a target. We show examples of such calculations for nitrogen impinging on gold (Fig. 1) and steel (Fig. 2). These figures show the relative number of backscattered particles calculated as a function of energy for different values of the incoming beam. For N on Au, the outgoing beam is peaked at about 70% of the incoming energy, while for N on Fe this value is reduced to 35%. The backscattered particles come off with a $\cos\theta$ distribution, so that the beam is somewhat forward peaked. We estimate the neutral flux produced in ACT-1 as follows. The ion source from the entire plasma, S_i , can be estimated as

$$S_i = \frac{nV_p}{\tau_c} = 1 \times 10^{20}/s, \quad (1)$$

where τ_c is the confinement time, and n and V_p are the plasma density and volume, respectively [see Table 1 for the values used in Eq. (1)]. The neutral source, S_n , depends on the fraction of ions that intersect the biased limiter as they drift outward. Ions from the center of the plasma travel

roughly half way around the torus in the time they drift radially outward. By inserting the biased limiter a few centimeters into the plasma, up to a third of the particles can be intercepted. In practice, the port opening to the drift tube restricts the fraction that can be used to approximately a quarter of the ion source. The energy will depend on the bias voltage applied to the limiter. The flux onto the sample depends on the fraction of neutrals reflected into a solid angle at the end of the drift tube. Though the TRIM code predicts about 80% reflection, we assume 50% to make a conservative estimate of the neutral flux. The reflected particles cover an area $\Omega_s \approx \pi d^2$ where d is the distance from the limiter to the sample. The flux on a target located 1 m away is

$$\Gamma_n = \frac{S_n}{\pi d^2} \sim 5 \times 10^{14} / \text{cm}^2 / \text{s} . \quad (2)$$

A 1-A plasma current would result in a beam flux of $\approx 5 \times 10^{14} / \text{cm}^2 / \text{s}$ at a distance of 100 cm from the limiter, covering an area of $\sim 100 \text{ cm}^2$. In this way a substantial flux of low energy particles can be directed onto a target.

B. Description of Facility and Diagnostics

The glow facility consists of a toroidal plasma source (ACT-1), a limiter for converting the plasma ions into neutrals, and a drift tube for the beam. Figure 3(a) shows a photograph of the facility and Fig. 3(b) shows a vertical cross section of the apparatus. In Tables 1 and 2, we list some of the plasma and drift tube parameters. The limiter, consisting of tungsten, stainless steel, or gold-plated copper plates fastened to a wedge-shaped (as viewed from the top), water-cooled copper core, is surrounded by a nitrogen or dry air plasma. The plasma, created by ionizing collisions between a 400-V electron

beam and the background gas, surrounds the limiter on all sides. Plasma ions are accelerated across a sheath into a negatively biased limiter (0-150 V) placed on the outside of the toroidal plasma. The neutralized ions pass through a 10-cm aperture into the 80-cm-long drift tube.

The drift tube has a separate 450 l/s turbo pump. Gate valves at the entrance to ACT-1 and the pump allow quick changes in the drift tube without breaking vacuum in ACT-1. Gases such as nitrogen, air, NO, and CO are added to the observing volume through the vertical tube and valve.

Light emitted in the drift tube is measured by a lens and photomultiplier tube at the first port cross. To reduce the intensity of the stray light into the optical system, we placed a light dump (a blackened teardrop-shaped glass called a Wood's horn) opposite the light observation port. Coarse spectral resolution has been achieved using interference filters (70-nm width) or a variable filter in front of the photomultiplier tube. Targets of various sizes and composition can be moved along the axis of the drift tube by a rod inserted through a Wilson seal at the end of the drift tube. The target can also swing out of the beam by use of a hinged mechanism operated by moving a second rod through a Wilson seal.

We employed a Langmuir probe, located on one of the top ports, to detect background plasma in the tube. Detectors for neutral beams with energies less than 100 V are not readily available. We attempted two methods of monitoring the beam, neither of which behaved as anticipated. These were a pyroelectric detector on the end flange and a nude gauge mounted on a bellows on a side port. Data obtained from them are discussed later, but are not used for our analysis of the beam or glow.

III. RESULTS AND DISCUSSION

A. Surface-Induced Glow

We exposed a number of targets to nitrogen beams at various values of the limiter bias voltage. The presence of the target resulted in an enhancement of the photon flux in the viewing volume, which we characterize as a surface-induced glow. At this early stage of our work we still need to obtain more data to determine the mechanisms involved in producing the glow. In Fig. 4, we show relative surface glow intensity as a function of distance from a target coated with Z-306 paint, and a limiter bias of 100 V (which according to the TRIM code corresponds to beam particles with energies of 30 eV to 50 eV). The light intensity decreases over a distance of 10 cm with a scale length of approximately 1.5 cm.

To rule out the possibility that the light signal in front of the target was caused by reflections of plasma light from the target or from the drift tube walls, we examined the viewing volume seen by the phototube. By varying the axial position of a point source centered in the drift tube and recording the photodetector signal until the reading dropped to zero, we determined the area at the center of the drift tube visible to the photodetector. We repeated the experiment with the light source located on the opposite side of the drift tube from the photodetector, allowing us to determine whether light scattered from the walls could be seen by the detector. These tests indicated that at the center of the drift tube the photodetector sees an area of less than one centimeter square and the total projected viewing area was well within the light dump opposite the detector. Thus, with the target a few centimeters back from the photodetector, reflected light would not be visible, suggesting that any signal seen in front of the target should be genuine. This conclusion is borne out by the discovery (discussed in C) that the light in the drift tube is delayed with respect to the light from the plasma.

In Fig. 5, we show the results for a target coated with Z-302 paint using limiter bias voltages of 25 and 7.5 V corresponding to average beam energies of about 10 eV and 4 eV, respectively. We estimate the decay lengths to be 2.5 cm and 1.5 cm for these two energies. Overall, when the target is moved close to the viewing volume, there is a 10-30% enhanced emission, depending on energy. From preliminary spectral studies using broad-band filters, we find variations of the spectra as a function of energy. It is too early to know the origin of these changes without higher spectral resolution. The spectra and scale length of the glow may be different from the spacecraft glow because of the absence of oxygen in these studies. However, nitrogen interactions have been proposed as a source of glow on spacecraft [1, 5, 6].

B. Neutral Beam Diagnostics

The nude gauge was intended to measure small changes (a few parts in 10^4) in the gas density accompanying the beam. Signals of approximately 100 times this level were observed on the ionization collector. The signal consisted of both a slow (~ 50 ms) and a fast component. The former is consistent with the expected pressure buildup from the beam. The latter may be caused by plasma formation in the duct; a plasma density of 10^4 cm^{-3} would account for the observed signal.

Pyroelectric crystals respond quickly to small changes in temperature by driving a current across a load resistance and can be used to measure the beam power. In addition to particle energy, they are sensitive to photoelectron emission and radiation heating. We observed large signals on this detector after installation, and we determined that most of it was caused by secondary electron emission with the remainder dominated by UV radiation from the plasma. Efforts continue to improve the sensitivity and reduce the noise background in the detectors.

C. Time Delay Data

Study of the time delay between extinction of the beam (during pulsed operation of the plasma) and light decay at the limiter may provide clues regarding the source of the emission. The light signal, if viewed directly on an oscilloscope, is too noisy to determine time delay with any precision. We time-averaged the signal over many pulses, using a boxcar integrator for this purpose.

The top of Fig. 6 shows the fall-off of the direct light emission from the plasma as measured by the boxcar integrator. The turnoff time coincided with the corresponding time for decay of the limiter current. Light from the drift tube, however, is delayed with respect to the direct emission from the plasma, as shown in the lower traces of the figure. As the limiter bias was raised above 0 V, where the time delay was negligible (not shown), the emission from the drift tube developed a tail with a decay time of 500 μ s. Higher bias yielded a larger fraction of delayed light. In the bias range between 100 V and 150 V, there was a time delay of 200 μ s before the development of the characteristic tail.

The most clear-cut conclusion to be drawn from these data is a negative one: the light is not merely radiation from the plasma that undergoes multiple reflection along the drift tube. The reason for the delay is not clear at present. The 200 μ s delay, if interpreted as the time of flight of the beam particles, would yield a translational energy of only 3.3 eV for N_2 . This energy is so small compared with the bias voltage that the interpretation seems unlikely. The long time constant for decay could imply the existence of metastable states that do not quench on one collision with the walls, since the average time for wall collision would be 100-200 μ s. Other explanations must be investigated.

The composition of the beam has not been determined. The underlying physics of beam formation suggests that the beam is predominately composed of N atoms and N_2 molecules in their electronic ground states. Metastable electronic states may also be present in the beam and may play a role in light emission in the drift tube. In addition, highly excited vibrational and rotational states of N_2 may also be important in reactions in the drift tube. If metastables are a significant fraction of the beam, we can attempt to remove this component by optical pumping of the beam upstream from the target. If the pressure in the drift duct can be lowered to $\sim 10^{-5}$ Torr strong electric field pumping of this region may also be implemented.

D. Volume-Produced Glow

Most of the background light in our drift tube is produced by the beam interacting with gas molecules. At room temperature, the drift tube pressure, 10^{-4} Torr, corresponds to a molecular density of $3 \times 10^{12} \text{ cm}^{-3}$. The incoming beam can interact with these molecules and produce radiation through excitation or gas phase chemical reactions. This intensity can be used to estimate the beam flux, which was not possible to do with the nude gauge or pyroelectric detector. After sufficient beam characterization, the ACT-1 facility could be used to study neutral-neutral gas phase scattering and interactions at low energies, which is important to upper atmospheric physics, atomic physics, and chemistry.

Figures 7 and 8 show light intensity as a function of drift tube pressure for a variety of added species (N_2 , dry air, CO, He, and NO). For all gases, except helium, the emission increases linearly with pressure to $\sim 5 \times 10^{-4}$ Torr, where it levels off and then decreases at higher pressures. For a beam attenuated by passing through a column of target particles (see Fig. 9), this

intensity behavior is the anticipated result. The intensity, $I(x)$, in the viewing volume at a distance x from the beam source is proportional to the density as,

$$I \propto n_t \sigma_{ex} \Gamma(x), \quad (3)$$

where

n_t = number of target particles ($\propto$ pressure),

σ_{ex} = excitation cross section,

$\Gamma(x)$ = flux of beam particles at x .

The beam attenuation can be approximated as,

$$\Gamma(x) = \frac{\Gamma(0)}{(x/x_0)^2} \exp(-n_t \sigma_{tot} x), \quad (4)$$

where σ_{tot} is a sum over all reactive and scattering processes, $\Gamma(0)$ is the flux at the limiter, and $x \gg x_0$, with $x_0 = 3-6$ cm, indicating the far field region of the beam. The value of σ_{tot} can be estimated by solving for $\partial I / \partial n_t = 0$, yielding $\sigma_{tot} \approx 1/n_t x = 10^{-15} \text{ cm}^2$, which is a characteristic value for such processes. The insensitivity to the helium pressure suggests that most of σ_{tot} may be due to reactive processes.

We have also studied the light emission as a function of limiter current for a fixed bias voltage. The limiter current changes with the intensity of the plasma source; we vary the plasma current by adjusting the high voltage electron beam that ionizes the gas in ACT-1. The results for $V_L = 100$ V in Fig. 10 show a linear behavior between phototube current and limiter current, another indication that the light in the drift tube results from the neutral

beam interactions rather than reflected or fluorescent scattering of plasma light.

In Fig. 11, we show the dependence of the volume glow intensity with bias voltage, assumed to reflect the dependence on beam energy. This example is for a nitrogen beam impinging on air at three different pressures. The general behavior of the intensity with increasing bias voltage is a small increase in photomultiplier tube current to approximately 40 V, after which there is a larger, nearly linear increase. At zero bias voltage the photomultiplier tube current is much larger than the dark current, thus indicating that a volume glow is present. One reason for this emission is that the limiter has a sheath potential of a few electron volts due to the interception of the plasma even when no external bias is applied. In this situation a beam of neutrals with a few electron volts is produced in the drift tube and these can react with the target gas to produce emission. This background glow is not necessarily due to excitation (the energy is low), but is probably from gas phase reactions, so we assume that the glow due to excitation goes to zero at low bias voltage, and have drawn σ_{ex} going to zero at this background level. If the volume source is assumed to be from excitation of the target atoms by the nitrogen beam, then the beam flux can be estimated. We use the ionization cross section for N_2 on N_2 [10] to estimate σ_{ex} at low energies. The functional dependence shown in Fig. 11 is similar to the behavior of the phototube current.

At a wave number of 750 ± 100 nm, for a Hamamatsu R928 photomultiplier tube biased at 1000 V, we estimate that 1 nA corresponds to volume emissivity of 1.1×10^5 photons/cm³/s (the dark current in the tube is 3.5 nA). Typical observed emissivities for the volume glow at $P = 10^{-4}$ Torr are about 10^8 photons/cm³/s. The beam flux can be estimated from the intensity of the volume glow from

$$R = n_t \sigma_{ex} I \quad (5)$$

With a target gas of dry air at 5×10^{-4} Torr, a stainless steel limiter biased to 100 V, collecting 1 A, with a 2.5-cm-diameter baffle in front of the limiter, $R = 1.3 \times 10^9$ photons/cm³/s. This emissivity yields a beam flux of 5×10^{13} /cm²/s assuming an excitation cross section, $\sigma_{ex}(50 \text{ eV}) = 1.6 \times 10^{-18}$ cm², (about twice the ionization cross section). With the baffle removed to take full advantage of the limiter, the calculated flux would increase above 10^{14} /cm²/s, in reasonable agreement with the predictions of the TRIM code.

E. Spectra

The light levels proved to be too low to allow resolution of the spectra of the volume emission by DC operation of a 0.3-m-grating spectrometer. Instead, we obtained coarse spectra (bandpass of 70 nm FWHM) pointwise by filter/photomultiplier tube combinations.

Figure 12 shows the spectra for various conditions. There are several maxima from 400-700 nm, but at this resolution, positive identification of the features is not possible. There are a number of candidates among atomic NI lines, N₂ 1st positive, N₂ 2nd positive, other N₂ systems, and possibly even NO bands. The relative intensities of these maxima appear to be sensitive to the target gas pressure and species. Figure 13 shows the result of using NO and CO as target gases. The N₂ on CO emission spans several CO band systems (Comet Tail, Triplet, Asundi, Herzberg, and Angstrom bands) which might account for the broad continuum-like appearance at this resolution. Extension of the comparison of N₂ on N₂ and N₂ on CO into the near infrared are shown in Fig. 14. In this region N₂ 1st positive and N₂ infrared bands would be expected to make large contributions to the emission. Higher resolution

spectra of such emissions are necessary to identify the mechanisms of photon production. Attempts can then be made to determine rate coefficients for these various excitation and reaction mechanisms in the interesting and previously inaccessible energy regime of 3-20 eV.

IV. SUMMARY

We have produced in the laboratory a surface-induced glow due to the interaction of a beam of nitrogen with targets consisting of Z-302 and Z-306 paints. The glow intensity decreases with distance from the target with a scale length of ~ 2 cm; the glow can be detected to several centimeters. We estimate that beam fluxes $> 10^4/\text{cm}^2/\text{s}$ were achieved on the target, and we were able to vary beam energies from a few to ~ 50 eV. We lack detailed spectroscopic information which would shed light on the mechanisms responsible for the glow. The scale length of the surface glow we observe is different from that encountered in spacecraft glow and is perhaps due to the absence of oxygen in our beam. We expect to study the surface glow with an air plasma in ACT-1 in the near future.

We have also discovered a volume glow due to beam particles interacting with a variety of target gases in the drift tube. Both nitrogen and air beams were used in this work. The intensity of the volume glow is such that it should contribute to the spacecraft glow. The volume glow in the spacecraft environment would be due to pressure buildup on the ram surface of the craft. Flux conservation requires that the density increase at the surface if the gas particles leave with energies lower than that of the incoming beam. If the gas leaves the surface with surface temperatures a factor of ~ 20 , enhancement could be present. The volume glow component would scale with the

square of atmospheric density since both the incoming beam flux and ram pressure enhancement scale with density. Recent studies of the glow on Atmospheric Explorer Satellite [1] indicate that the glow has two components; one of which scales with the nitrogen density squared. This variation is precisely that predicted by our studies of the volume glow and is consistent with our conclusions based on the laboratory studies.

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TABLE 1

Physical and Plasma Parameters of ACT-1

Minor Radius	10 cm
Major Radius	50 cm
Plasma Radius	7 cm
Gas Pressure	$\sim 2 \times 10^{-4}$ Torr N_2 or Air
Electron Density	$(1-5) \times 10^{12} \text{ cm}^{-3}$
Ion Temperature	1-5 eV
Confinement Time (τ_c)	1 ms
Limiter	Tungsten, Stainless Steel, or Gold
Limiter Current	1-5 A
Particle Flux	$(0.7-3.5) \times 10^{19}/100 \text{ cm}^2$

TABLE 2

Drift Tube Parameters

Gas Pressure	$\leq 10^{-4}$ Torr
Particle Flux (65 cm from limiter)	$(1-6) \times 10^{14} \text{ cm}^{-2} \text{ s}^{-1}$ For N_2 Beam
Filling Gas	N_2 , Air, CO, NO, and He

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Figure Captions

- Fig. 1. Predicted energy distributions of 20 eV and 40 eV N atoms backscattered from an Au surface. The N atoms impacted at normal incidence and their backscattered angular distribution was close to $\cos\theta$ where θ is the angle from the surface normal. The total backscattered yield was about 70% in each case. These results were obtained with the TRIM code.
- Fig. 2. Predicted energy distribution of 5, 10, 20, and 40 eV N atoms backscattered from an Fe surface. The N atoms impacted at normal incidence and their backscattered angular distribution was close to $\cos\theta$, where θ is the angle from the surface normal. The total backscattered yield was about 70% in all cases. These results were obtained with the TRIM code.
- Fig. 3. (a) A photograph of the ACT-1 vessel with the drift tube attached to one port. The components and diagnostics are indicated on the schematic shown in Fig. 3b. (b) Sketch of the glow facility, showing a cross section of the toroidal ACT-1 plasma, the limiter, and drift tube, diagnostics, and gas supply system for the drift region.
- Fig. 4. The photo flux as a function of distance from the target (the target is on the left and the beam arrives from the right side). The target surface is coated with Z-302 paint, the limiter bias is 100 V, and the plasma in ACT-1 contained nitrogen. The volume glow

background has been subtracted. Open circles indicate data taken with the turbo pump on and a drift tube pressure of $1.5 \cdot 10^{-4}$ Torr; the solid circles correspond to data taken with the pump off and a pressure of 2.5×10^{-4} Torr. Even though the volume glow is different in each case, the surface glow remains unchanged, showing that the decay is a function of the beam striking the surface and not some interaction mediated by the volume.

Fig. 5. Same as Fig. 4 except that the target is coated with Z-302 paint and two different bias voltages are shown. We plot the relative intensity ΔI which is the surface glow divided by the limiter current to correct for changes in plasma current. A nitrogen plasma was used for both these measurements.

Fig. 6. Time variation of light signals from the plasma (top trace) and the drift tube (two bottom traces) after termination of the plasma. The numbers refer to the limiter bias in volts.

Fig. 7. Photomultiplier tube current versus gas pressure in the drift tube for a variety of fill gases. The limiter bias was set to 100 V and no filter was used in front of the detector. A nitrogen plasma was used in all cases.

Fig. 8. Same as Fig. 7 for a dry air plasma. We did not use spectral filters for these measurements and the photomultiplier tube was sensitive to wavelengths over the range 2000 Å to 7000 Å.

Fig. 9. Schematic model of a reactive neutral beam traversing a column of target gas in the drift tube. This model explains the behavior of the results shown in Figs. 7 and 8 and is discussed in detail in the text.

Fig. 10. The photomultiplier tube current (proportional to the volume glow emissivity) is linear with limiter current showing that the beam flux is proportional to the limiter current. For this experiment the limiter bias was 100 V and the limiter current was varied by changing the voltage on the electron beam used to create the plasma in ACT-1.

Fig. 11. Here we show the photomultiplier tube current (proportional to volume glow emissivity) versus bias voltage for three drift tube pressures where the plasma is nitrogen and the fill gas is room air. The dashed curve shows the functional dependence of the $N_2 - N_2$ ionization cross section (right-hand scale) as a function of energy in electron volts (replace bias voltage by the label energy in electron volts). The cross-section scale was adjusted to fit the 5×10^{-4} Torr data at 150 V in order to show the similarities between the phototube current and cross section with energy. The cross section is assumed to go to zero at 15 V bias and the zero level is set to the background emission measured for zero bias voltage (see text for discussion).

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Fig. 2

Fig. 3(a)

Fig. 12. Phototube current, corrected for tube and filter response versus wavelength for combinations of a beam from a nitrogen plasma colliding with various background gases (0 V, 150 V). The x cases are for no gas added to the drift tube; gas flow between ACT-1 and the drift tube yields a drift tube density of $8.5 \times 10^{12} \text{ cm}^{-3}$, N_2 . The other cases (O,●) show the result of adding air to the drift tube.

Fig. 13. Same as Fig. 12 with N_2 beam from ACT-1. The N_2 density in the drift tube is $8.5 \times 10^{12} \text{ cm}^{-3}$ for all cases shown. Shown are the results of adding CO (□) and NO at two different pressures (O,●).

Fig. 14. Same as Figs. 12 and 13, but extended further into the infrared. The squares are for $1 \times 10^{13} \text{ cm}^{-3}$ added CO as shown in Fig. 12. Data to nearly a wavelength of 700 nm are obtained with a variable filter. Beyond 700 nm, data are from discrete bandpass interference filters. All data beyond 700 nm are normalized to yield a value of 10 at 759 nm for the CO (□) case. The radiometric efficiencies of the two filters were estimated from nominal filter parameters and so the connection between the sets of curves may be inaccurate by $\pm 25\%$.

Fig. 1

Fig. 3(b)

Fig. 4

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Fig. 5

#85P0236

Fig. 6

Fig. 7

Fig. B

#85P0243

Fig. 9

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Fig. 10

Fig. 11

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Fig. 12

Fig. 13

Fig. 14

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