A GROUND-BASED EXPERIMENTAL TEST PROGRAM TO DUPLICATE AND STUDY THE SPACECRAFT GLOW PHENOMENON

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Abstract. We discuss the use of a plasma device, the Advanced Concepts Torus-I, for producing atoms and molecules to study spacecraft glow mechanisms. A biased metal plate, located in the plasma edge, will be used to accelerate and neutralize plasma ions, thus generating a neutral beam with a flux $\gtrsim 5 \times 10^{14}/\text{cm}^2/\text{sec}$ at the end of a drift tube. Our initial experiments will be to produce a 10 eV molecular and atomic nitrogen beam directed onto material targets. Photon emission in the spectral range 2000 to 9000 Å from excited species formed on the target surface will be investigated.

Introduction

The Advanced Concepts Torus-I (ACT-I) will be used at the Princeton Plasma Physics Laboratory to produce a source of neutral atoms and molecules to study spacecraft glow. In this paper, we list the characteristics of the machine and describe the experimental arrangement and research program. We estimate that this plasma device can be used to produce the flux of neutrals on a sample located in a test chamber outside ACT-I greater than $5 \times 10^{14}/\text{cm}^2/\text{sec}$, similar to that encountered in the environment of the Atmosphere Explorer satellite and the space shuttle. We made spectroscopic studies of a nitrogen plasma in ACT-I and detected emission from N_2 and N_2^+. Preliminary experiments have been conducted using a small biased limiter to generate neutrals, and the measured currents are consistent with our predictions that ACT-I has the properties to produce the desired neutral flux.

The ACT-I Device

ACT-I is a steady-state toroidal machine (Figure 1 and Table 1) built primarily to study radio frequency heating and current generation in plasmas [Wong et al., 1981]. The characteristics of the plasma formed in ACT-I are such that it can be converted into a copious source of neutrals with energies of 3 to 100 eV. The plasma characteristics for both steady-state and pulsed operation are given in Table 1. The machine consists of 26 sets of toroidal field coils which produce up to a 5.5 kg steady-state magnetic field. The vacuum chamber has 26 toroidal segments with large ports (10 cm x 40 cm). A 600 kW motor-generator set provides steady-state power to the coils which are cooled by pressurized de-ionized water. ACT-I has been operated with a variety of gases, including H, He, Ne, Ar, N_2, and air.

A Neutral Source

Ions formed in ACT-I are confined for about 1 msec and most of them are lost by drifting radially outward across field lines onto the outer wall. A fraction of these ions (~0.3) can be intercepted on a metallic plate, a so-called limiter, where they are neutralized and reflected. A calculation of reflectivity of neutrals formed in this manner using the TRIM code [Biersack and Haggmark, 1980] predicts that a high percentage of the incoming particles is 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 (Figure 2). A target will be mounted in a test chamber at the end of this tube and the glow resulting from the neutral-surface interaction will be observed in this chamber. The limiter may be biased to accelerate the ions and produce neutrals with an adjustable range of energies.

Estimate of Neutral Flux

What makes this device an effective plasma source for the glow problem is that it can sustain a dense plasma with a warm bulk ion temperature (T_i > 1 eV), with sufficient volume, to produce a large steady-state source of plasma with T_e = 1 to 15 eV. The plasma source can readily be converted into a large flux of energetic neutrals as described above. The ion source from the entire plasma, S_i, can be estimated as

$$S_i = \frac{nV_p}{\tau_c} = 1 \times 10^{20}/\text{sec} \; , \qquad (1)$$

[see Table 1 for the symbols and 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 about 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 about 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, Ω_s. The reflected particles are forward-peaked giving $\Omega_s \approx \pi d^2$ where d is the distance from the limiter to the sample. Though the TRIM code predicts about eighty percent reflection, we assume only fifty percent to make a conservative estimate of the neutral flux. Therefore, $S_n \approx S_i/8$, and the flux on a target located 1 meter away is

$$\Gamma_n = \frac{S_n}{\pi d^2} \sim 5 \times 10^{14}/\mathrm{cm}^2/\mathrm{sec} \ . \qquad (2)$$

Diagnostics and Spectroscopy

We will install diagnostics to look at the plasma source, the energetic neutrals in the drift tube, and the molecular emission in the test chamber. The plasma temperature and density are measured with a triple Langmuir probe and microwave interferometer; the spectroscopic signature of the plasma is also monitored. This information is needed to optimize the plasma for production of neutrals and identification of any contribution of the plasma light to the background in the test chamber.

Screening of Background Light and Velocity Selection

In the test chamber, it is crucial to screen out the background plasma light. An effective technique for screening is to use a rapidly rotating slotted chopper disk on the port end of the drift tube (Figure 2) [Voss and Cohen, 1982]. The flight time for 5 to 10 eV neutrals down a 1-meter tube is about 100 microseconds, and the rotor speed must be about 10,000 rpm for the configuration used here. The chopper can be used as a velocity selector if two slotted disks are mounted with a phase shift between the slots in the blades. Such devices have been built at PPPL and used for experiments with hydrogen neutrals produced by charge exchange within the Princeton Large Torus. The following techniques will also be employed to reduce the background light: (1) the position of the biased limiter over the port will obscure the line-of-sight to the bulk of the plasma (Figure 2), and (2) baffles in the drift tube to block light reflections. The sample will be mounted perpendicular to the drift tube and the line-of-sight will graze the target and pass into a light dump so that only photons from the glow should be detected. Prior to the installation of a rapidly rotating chopper a slow chopper containing open and glass slots can be used to subtract any remaining background light.

Spectroscopy

We estimate a photon source in the visible of 5×10^{10}/sec produced on a sample with an area of 10^2 cm^2, assuming an efficiency of photon production in the visible of 10^{-6} due to the interaction of the neutrals with the surface. Because most of the glow will appear within 10 cm of the target surface, the photon production rate coefficient within the emitting volume (10^3 cm^3) is $\phi = 5 \times 10^7/\mathrm{cm}^3/\mathrm{sec}$. We shall use calibrated interference and/or color filters with photomultipliers for initial, sensitive broadband detection of glow effects. The sample will be viewed at different angles from 2000 to 9000 Å using two or more calibrated Czerny-Turner spectrometers. The spectra from a 1 cm wide slice of the volume will then be measured with 25 Å resolution using a f/4.8, 0.32 m monochromator with a 1200/mm grating. With this configuration the counting rate in the visible should be 4×10^2 pulses/band/sec assuming a detector quantum efficiency of 0.1 and a light source spread uniformly over a hundred bands from 3500 to 6000 Å. A larger counting rate is expected in the infrared regime, 6000-9000 Å, because the increased photon production due to the neutral-surface interaction will more than offset the decrease in detector sensitivity. Once any glow has been detected, we will observe the spectra with higher resolution and extend the observations into the infrared to 2 microns.

Characterization of the neutral beam is important and an in-line quadrupole mass spectrometer will be employed at the end of the drift tube to determine the relative concentration of atoms and molecules. Initially, the beam intensity will be estimated by the rise in gas pressure at the end of the drift tube. Later we will install a direct low-energy beam monitor, such as a pyroelectric detector.

Experimental Results

Our spacecraft glow experiment began in mid-April and, presently, we are studying the operation and characteristics of a nitrogen plasma. The spectrum of an ACT-I nitrogen plasma over 5000-9000 Å with 8 Å resolution is shown in Figure 3. Structure of bands from the first positive system of N_2 can been seen clearly between 5500 and 8000 Å. The spectrum shown here rolls off above 9000 Å because the GaAs photomultiplier loses sensitivity and below 5000 Å because a long pass filter with a 5000 Å cutoff was used to eliminate higher order signals in the spectrum. The figure includes a relative sensitivity curve, which must be multiplied by the spectrum intensity to give the relative intensity of the plasma light as a function of wavelength. Higher resolution spectra at 3500-4200 Å (Figure 4) show the first negative spectrum of N_2^+ and the second positive spectrum of N_2. We also see in this figure features which may tentatively be identified as belonging to CN and trace amounts of other carbon containing species. The temperature and density of the bulk plasma in these discharges were $\sim 3 \times 10^{12}$ cm^{-3} and $T_e \sim 5$ eV, and the N_2 filling pressure was $\sim 1.6 \times 10^{-4}$ Torr. The plasma was operated in a pulsed mode with 10 ms pulses and a duty cycle of one-half driven by a 5 A electron beam produced by a filament biased to $\geq$ 200 V. Viewing the plasma by eye shows that the beam is responsible for a large fraction of the optical excitation observed in our data.

A test version of the biased limiter, 2 cm × 4 cm, was mounted near one of the ports during this startup phase. The current was measured on the limiter to determine the rate at which ions were neutralized. We measured about 1.2 amps of current on the limiter at 20 eV (this voltage should produce 10 eV neutrals), corresponding to a collection rate of 7.5×10^{18} ions s^{-1}, or 7.5 percent of the plasma ion source, S_i

[Equation (1)]. We estimate that the maximum plasma volume that this limiter could intercept corresponds to a collection efficiency of 15 percent, and, in practice, should be less. We conclude that the biased limiter is functioning as intended and that when we install a larger limiter a quarter of the ions will be collected in front of the opening to the drift tube.

The drift tube and sample chamber are under construction and will be installed in a few months along with spectroscopic diagnostics. Initially, measurements will be made to characterize the neutral source's composition, flux, density, and velocity, and for the presence of excited states. Various sample materials of the kind tested on spacecraft for glow will be mounted in the test chamber and exposed to the neutral flux. We will search for glow produced by the interaction of nitrogen on the surface and measure its intensity and spectral composition. The effect of impact energy on the glow will be studied by changing the biasing voltage on the limiter.

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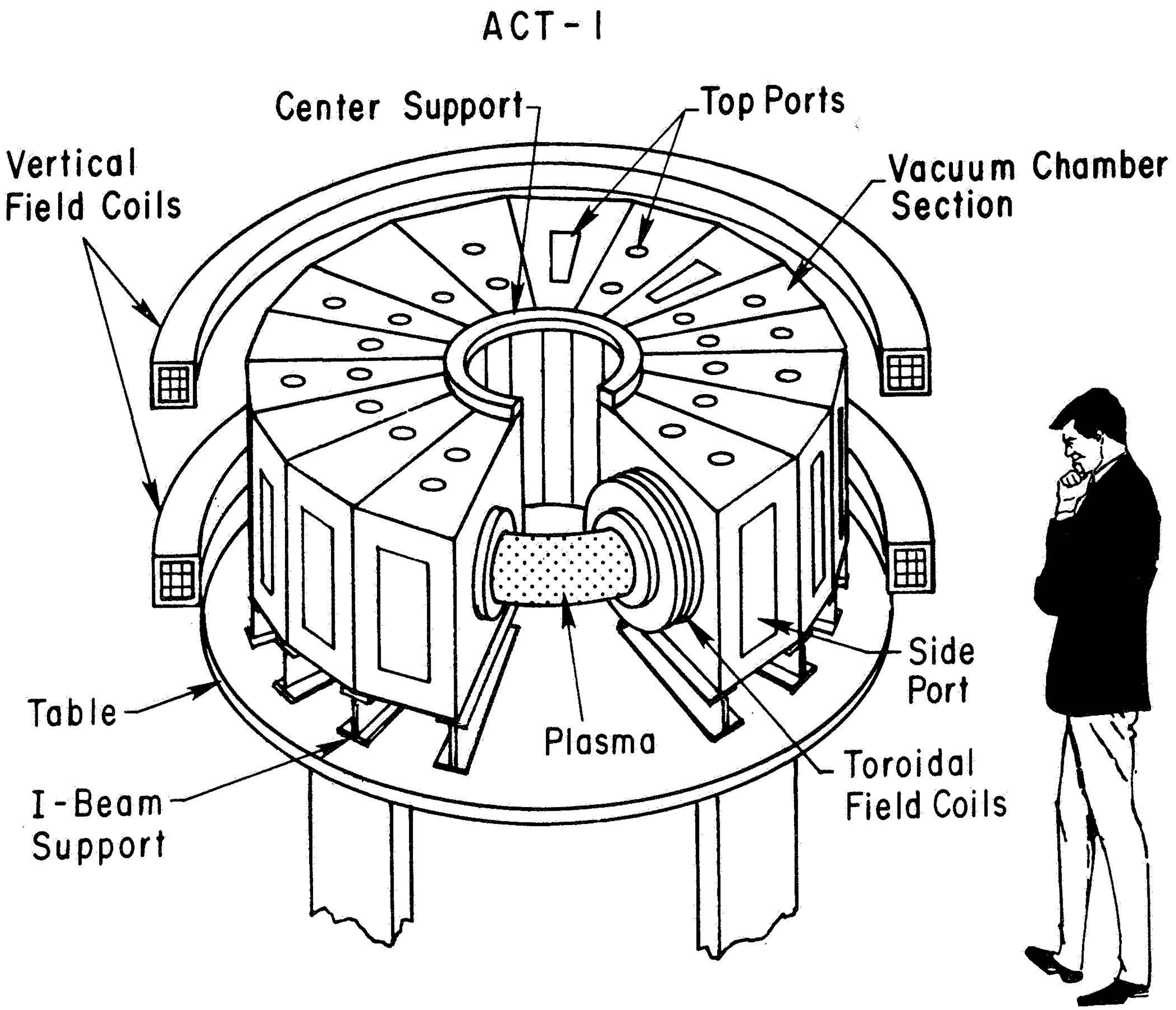

Fig. 1. Schematic of the ACT-I device.

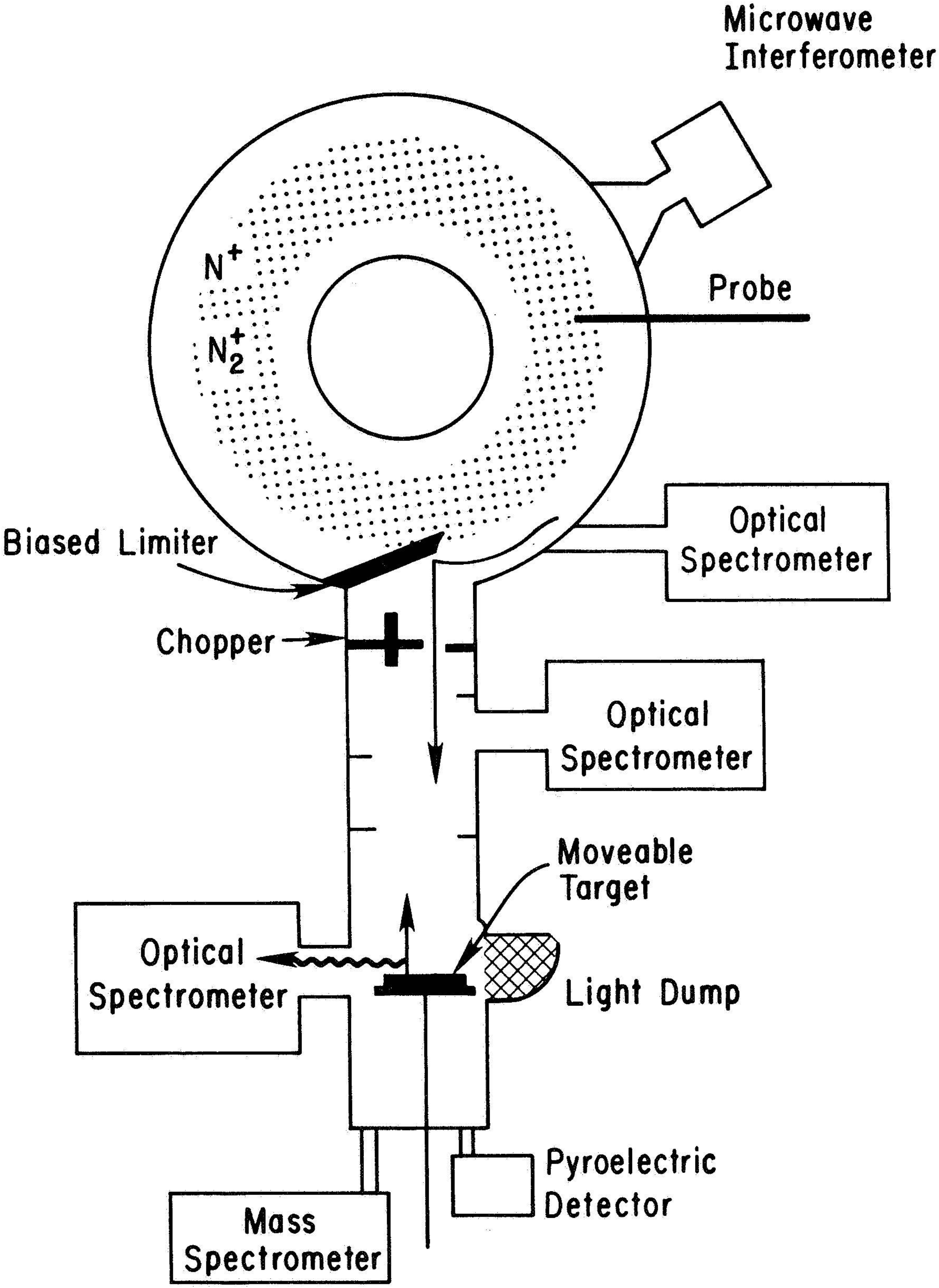

Fig. 2. Schematic of the experiment showing the drift tube, test chamber (not to scale), and diagnostics. The probe and interferometer measure the plasma density and temperature. Baffles (indicated by short lines on the sides) block reflected light.

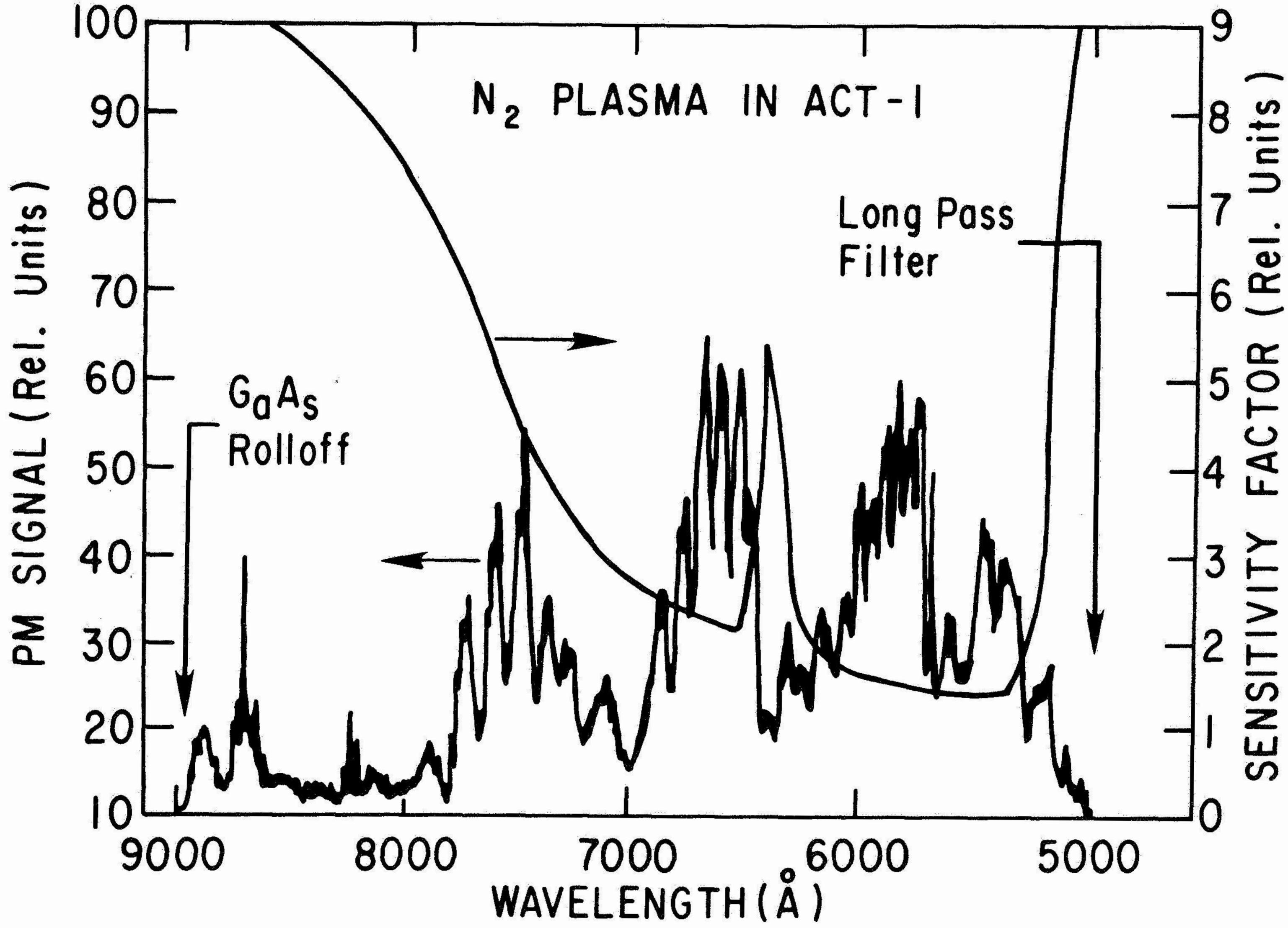

Fig. 3. The spectrum of a nitrogen discharge in ACT-I taken using a double monochromator with a FWHM bandpass of 8 Å. The multiplicative sensitivity factor can be used to scale the observed spectral intensity.

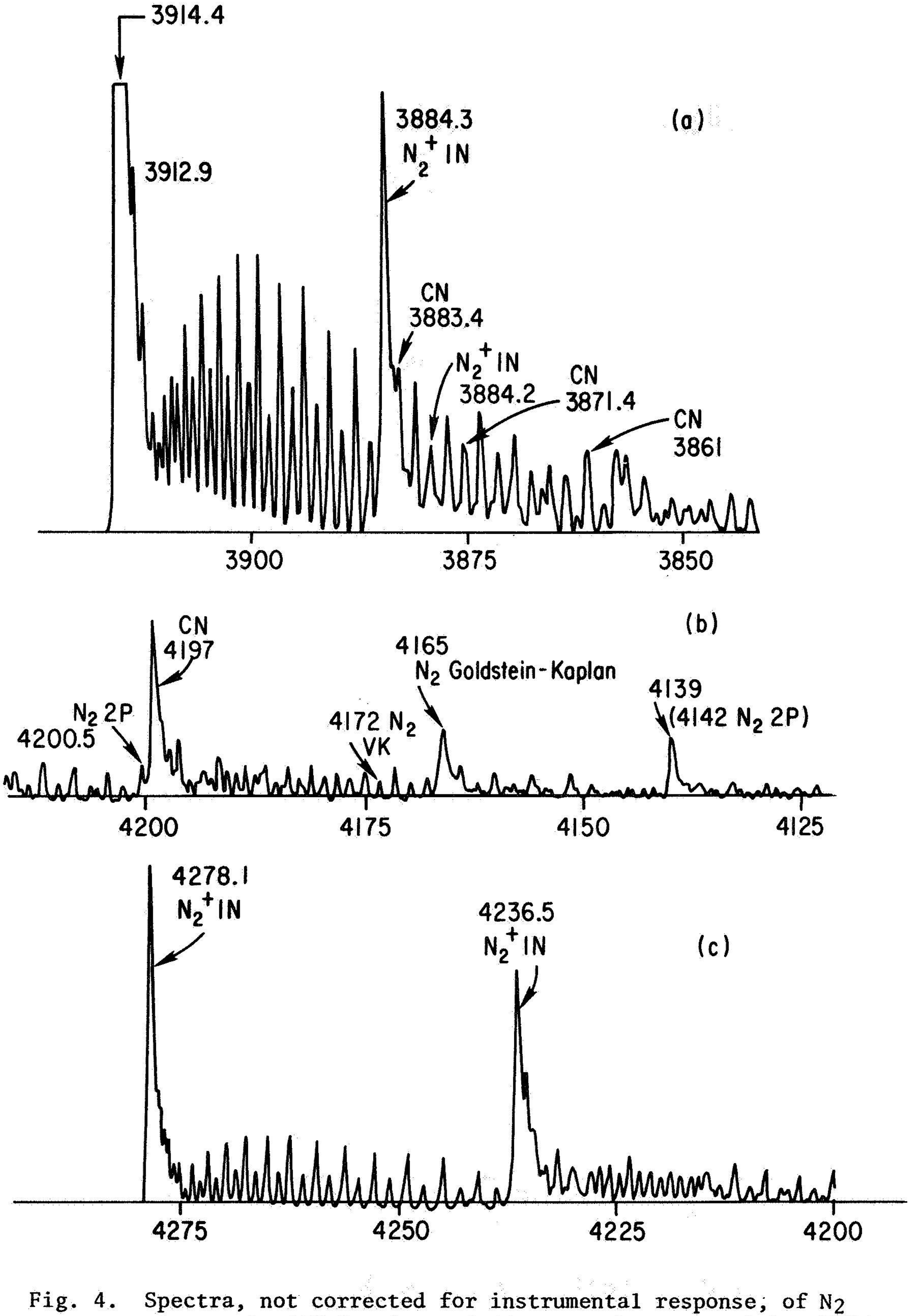

Fig. 4. Spectra, not corrected for instrumental response, of N_2 plasmas in ACT-I using a 0.66 m monochromator with a FWHM bandpass of 0.5 Å. The N_2^+ first negative (indicated by 1N) system dominates the spectrum. The shoulders on the 1N(1,1) band may come from CN emission.

TABLE 1. PHYSICAL AND PLASMA CHARACTERISTICS OF ACT-I

			Comments
r	Minor radius:	10 cm	
R	Major radius:	59 cm	
V	Volume:	1.2×10^5 cm^3	
r_p	Plasma radius:	7 cm	
V_p	Plasma volume:	6×10^4 cm^3	
n_e	Electron density:	10^{12} cm^{-3}	continuous operation
		10^{13} cm^{-3}	pulsed (20 μsec) with 20% duty cycle
T_e	Electron temperature:	$\leqslant$15 eV	up to 50 eV in the high energy tail
T_i	Ion temperature:	1-5 eV	without rf heating (in H_2)
τ_c	Confinement time:	1 msec	