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AURORAL N_2^+ ROTATIONAL TEMPERATURES OBTAINED WITH A SCANNING SPECTROMETER OF VERY HIGH SENSITIVITY

RICHARD SUTER

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ABSTRACT

A ground based 1m Ebert scanning spectrometer with high energy throughput for the study of aurora and airglow is described. Fully resolved N_2^+ 3914Å spectra with good signal-to-noise ratio are obtained in 13 seconds at an intensity of 30kR. Combination of the instrument with an electronic signal analyzer reduces the intensity requirements so that from N_2^+ 3914Å radiation of only 3kR such spectra are produced with an integration time of 14 minutes. Rotational temperatures derived from the observed spectra fall mostly in the region from 250°K - 500°K. A few spectra have been obtained showing a high temperature component in the range of 600° - 900°K. It is found that the intensity distribution of the rotational lines of the N_2^+ 3914Å auroral band is generally not simply proportional to the Boltzmann factor due to the extension of the auroral forms in height.

*Research Associate 1968-1970 of the National Academy of Sciences, Washington, D.C.

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1. INTRODUCTION

The determination of atmospheric temperatures from the intensity distribution in the rotational structure of the first negative N_2^+ bands observed in aurorae has become a standard technique since the early work of Vegard (1932). It is now well established that the N_2^+ rotational temperatures indeed represent true kinetic gas temperatures and that there exists a connection between the temperature and the height of the aurora (Vallance Jones and Hunten, 1960; Hunten, 1961). The more recent investigations mainly deal with the determination of the temperature gradient and with the study of rapidly changing auroral forms (Hunten, 1961; Johanson and Vallance Jones, 1962; Brandy, 1965).

It was common to all these investigations that due to the comparably low intensity of aurorae the rotational structure of the N_2^+ bands could only be resolved with photographic spectrographs after several hours of exposure (Vallance Jones and Harrison, 1955; Montalbetti, 1957). Obviously such spectra do not represent the temperature of a single auroral form, but are rather an average of several forms. Furthermore, from the experimenters point of view, the non-linearity between the incident radiation and the resulting density on the plate does not make data reduction straightforward. Energy limitation prevented all of the fast photographic and photoelectric spectrometers used up to the present time from resolving the rotational structure (Shepherd and Hunten, 1955; Johanson and Vallance Jones, 1962; Brandy, 1965). The temperatures then had to be determined from the profiles of the P- and R-branch. An interesting method for the instant determination of N_2^+ rotational temperatures has been developed by Hunten et al. (1963). They used two interference filter photometers each with a bandpass of about 10Å to monitor simultaneously the intensity of a portion of the P- and R-branch. The ratio of the two photometer outputs is a measure of the temperature, since the intensity of the rotational lines shifts towards higher rotational quantum numbers with increasing temperature. The instrument is calibrated in the laboratory with a N_2^+ light source. However, with this method a deviation of the rotational line intensity from a Boltzmann distribution does not immediately become evident. The energy throughput of the photoelectric spectrometer described below is sufficiently high that an acceptable signal-to-noise ratio for the fully resolved 3914Å N_2^+ band required an intensity of about 30kR. Much lower intensities could be accepted when the spectra of several scans were averaged with the aid of an electronic signal analyzer. By averaging, the signal-to-noise ratio is improved as $\sqrt{n}$, where n is the number of scans. Therefore a single scan at 30kR is equivalent to an average of 9 scans at 10kR or 100 scans at 3kR. Since the time required to scan the selected wavelength interval of 50Å is 13 seconds, the integration time is 2 minutes at 10kR and 22 minutes at 3kR. Under these circumstances temperatures can be determined with an accuracy of about 10°K.

2. INSTRUMENTATION

The spectrometer is a modification of a design by Fastie and is shown in Figure 1. It is of the Ebert type with a focal length of 1m. In order to point the instrument in any direction of the sky, it is suspended in a strong fork-mount. Fine adjustments in azimuth and elevation can be made with a motor drive.*

*The spectrometer was built by the Ray Lee Machine Company.

The circular entrance and exit slits are 15 cm long and their width can be varied in steps from 0.1 to 10 mm. The plane grating has 1200 grooves per mm and an effective area of 15.4 × 20.6 cm. It is blazed at 46° which corresponds to a wavelength of about 6000Å in the second and 4000Å in the third order. The dispersion at these wavelengths is 2.5Å/mm and 1.6Å/mm, respectively. The resolving power of the instrument is illustrated by the 3914Å N_2^+ band shown in Figure 2a which has been obtained with a laboratory hollow cathode light source and a slit width of 0.1mm. This spectrum is the average of eight spectra taken with the signal analyzer at a low light intensity.

The grating is driven in a saw-tooth mode by means of a uniformly rotating cam. The width of the scanned wavelength interval depends on the rise of the cam, while its location on the wavelength scale can be adjusted within certain limits by a micrometer device on the grating arm. The field of view perpendicular to the slit can be reduced from 10° to a fraction of a degree by using a telescope of 95 cm focal length in front of the entrance slit. A field lens and a conically shaped glass tube with an aluminized internal surface concentrate the light from the exit slit on the window of the photomultiplier. This detector is an EMR 541 R-type with its useful spectral sensitivity extending from 3000Å to 8500Å. A thermoelectric cooler is used to reduce the relatively high dark current to a tolerable level. At room temperature (24°C) and with a gain of one million the dark current is 2.6×10^{-9} amps. Cooling the cathode to -15°C reduces the dark current by more than a factor of 100 to 2.0×10^{-11} amps. The anode current of the photomultiplier is measured with a multiple range electrometer which produces an output voltage signal of 0-5 volts.

A Hewlett-Packard signal-analyzer operated in the averaging mode is used to improve the signal-to-noise ratio characteristics of the electrometer output signal when 3914Å radiation with an intensity of less than about 30kR is recorded. This instrument automatically averages succeeding signal forms. If the signal form is constant and superposed only by a noise component, then the noise component averages out to zero with increasing number of averaged signals. In our application the constant signal form is the spectrum of the periodically scanned wavelength interval. The signal analyzer is triggered by an optical shaft encoder rigidly connected to the shaft of the grating cam. This shaft encoder delivers 1024 count pulses per revolution in regular intervals as well as one separate synchronization pulse which triggers the start of the signal analyzer for each scan at exactly the same wavelength position. After receiving a count pulse from the shaft encoder the signal analyzer monitors the signal of the electrometer, takes the average of this signal with all previously recorded signals at this specific wavelength and stores the new average in one of its 1000 memory locations. The content of the memory is continuously displayed in the form of 1000 dots on a cathode ray screen and can be played back on a recorder after the averaging process has been stopped.

3. RESULTS

The spectrometer has been used for the study of N_2^+ auroral rotational temperatures in connection with rocket experiments from Fort Churchill, Canada. It was housed in a small astronomical type dome outside the auroral observatory of the Churchill Research Range about 10km from the launch site. The operation of the instrument at Churchill at all times had the character of a first extended field test. Since we soon realized that due to the extremely long slits the alignment of the spectrometer was most critical and varied considerably under changes of elevation we had to give up plans to observe aurorae in different parts of the sky. Therefore, the instrument was pointed all the time such that the 110 km intercept of the rockets was in the field of view and we were restricted to observe only those aurorae which appeared within the fixed field of view.

In Figure 2b the 3914Å band is reproduced as we have obtained it through a layer of fog during the night of Nov. 8-9, 1969, with a slit width of 0.2mm. The spectrum is the average of 64 scans equivalent to an integration time of 14 minutes and is of the low temperature type. In contrast, Figure 2c shows a spectrum of the high temperature type taken during the night of Jan. 14-15, 1970. This spectrum is also an average of 64 scans, but was taken with a slit width of 0.4mm. The intensity averaged around only 3kR thus giving a much poorer signal-to-noise ratio than in Figure 2b. Usually we worked with a slit width of 0.4mm which gave a sufficient signal-to-noise ratio from eight averaged spectra at an intensity of 12kR.

The rotational temperatures have been obtained from the intensities $I(N'')$ of the even numbered R lines according to the well known method by plotting the values $\log \frac{I(N'')}{N' + N'' + 1}$ as a function of $N'(N' + 1)$. Herein N' and N'' are as usual the rotational quantum numbers apart from spin in the upper and lower state of the molecule, respectively. If all radiating molecules are in thermal equilibrium this plot will be a straight line, the slope of which is inversely proportional to the absolute temperature. The value $B = 1.9898\ cm^{-1}$ for the rotational constant of the ground state of N_2 has been used as given by the tables of Wallace (1962). However, in this procedure overlapping of the first lines of the R-branch by lines of the returning P-branch has to be taken into account. From spectra taken at very high dispersion, e.g. the spectra published by Heath and Dieke (1958) it can be seen that in the dispersion of our instrument the R-lines from R(0) up to R(9) are overlapped by the P-lines P(27) up to P(36), respectively. Since in a $^2\Sigma - {}^2\Sigma$ transition the rotational line strengths of P- and R-lines originating from the same rotational level are almost equal,* it is indicated by the intensity of the R lines starting from R(25) whether a correction of the observed intensities of the first R-lines is necessary, and if so, what amount of correction has to be made.

When this graphical method is applied to the spectra of Figure 2, the three diagrams shown in Figure 3 are obtained. The spectrum from the hollow cathode light source yields an almost perfect straight line indicating a temperature of 740°K. The intensity distribution of the low temperature spectrum leads to two straight lines corresponding to temperatures of 255°K and 370°K, whereas in the case of the high temperature spectrum except for the lines R(2) and R(4) again one straight line indicating 500°K is obtained. The significance of deviations from a single straight line in the log $\frac{I(N'')}{N' + N'' + 1}$ plot will be discussed below.

During the nights from Nov. 7-8 until Nov. 9-10, 1969 and from Jan. 8-9 until Jan. 15-16, 1970, we have collected 70 averaged N_2^+ 3914Å spectra with sufficient signal-to-noise ratio to be able to determine rotational temperatures. However, rotational temperatures derived from these spectra are meaningful only if the total intensity of the band was constant or changed only very little during the

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*Tables and references of the rotational line strengths of many molecular electronic transitions are given by Schadee (1964).

period of averaging. In order to check this condition the signal of the spectrometer has been monitored continuously "real time" on a paper chart recorder. In addition, the time signal in the IRIG Standard Format C Code has been connected to the marker pens of the recorder.

It turned out that the total band intensity stayed reasonably constant for only 49 of the available 70 averaged spectra. Moreover, when $\log \frac{I(N'')}{N' + N'' + 1}$ was plotted, only about half of these bands yielded straight lines. The others gave either two straight lines, or could only be partially approximated by a straight line. From most of the straight lines temperatures between 250°K and 500°K were deduced which are within the limits of all earlier measurements.

A more unusual intensity distribution in the rotational line structure was recorded during the night of Jan. 14-15, 1970, when from 22:30 h until 01:15 h local time a diffuse glow was observed with the intensity continuously decreasing from 10kR to 3kR during that period of time. The averaged spectra then obtained are all of the high temperature type shown in Figure 2c. But only in a few cases the $\log \frac{I(N'')}{N' + N'' + 1}$ plot represents a single straight line. In most of these spectra the intensities of the R-lines with high rotational quantum numbers correspond to temperatures in the 600° - 900°K range compared to the temperatures around 500°K deduced from the first lines of the R-branch. In some cases the R-branch can even be followed up to R(28) beyond the head of the 1-1 band which is very unusual among all the spectra collected.

From our $\log \frac{I(N'')}{N' + N'' + 1}$ plots it became apparent that almost perfect straight lines as shown by the laboratory source in Figure 3a are very rarely obtained from auroral N_2^+ bands. A straight line seems to be only a good approximation in many cases. This behaviour is easily understandable from the fact that the aurora usually extends considerably along the line of sight and thus comprises atmospheric layers of different temperature and density. The variation of temperature and density with height can be taken into account mathematically fairly easily. However, in addition the excitation rate of N_2^+ ions as a function of height has to be considered which depends on the energy spectrum of the exciting particles. The excitation rate enters the calculation as a kind of weighting function for each layer but is difficult to determine due to its dependence on the energy spectrum of the exciting particles.

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REFERENCES

Brandy, T. K. Can. J. Phys. 43, 1697. 1965

Heath, D. F. and G. H. Dieke. Johns Hopkins Spectroscopic Report No. 16. 1958

Hunten, D. M. Ann. Geophys. 17, 349. 1961

Hunten, D. M., E. G. Rawson and T. K. Walker. Can. J. Phys. 41, 258. 1963

Johanson, A. E. and A. Vallance Jones. Can. J. Phys. 40, 24. 1962

Montalbetti, R. Can. J. Phys. 35, 831. 1957

Schadee, A. Bull. Astron. Inst. Neth. 17, 311. 1964

Shepherd, G. G. and D. M. Hunten. J. Atmos. Terr. Phys. 6, 328. 1955

Vallance Jones, A. and A. W. Harrison. J. Atm. Terr. Phys. 6, 336. 1955

Vallance Jones, A. and D. M. Hunten. Can. J. Phys. 38, 458. 1960

Vegard, L. Terr. Magn. Atmos. Elec. 37, 389. 1932

Wallace, L. Astrophys. J. Suppl. Ser. 6, 445. 1962

Figure 1. 1m Scanning Ebert Spectrometer Designed for Auroral and Airglow Studies

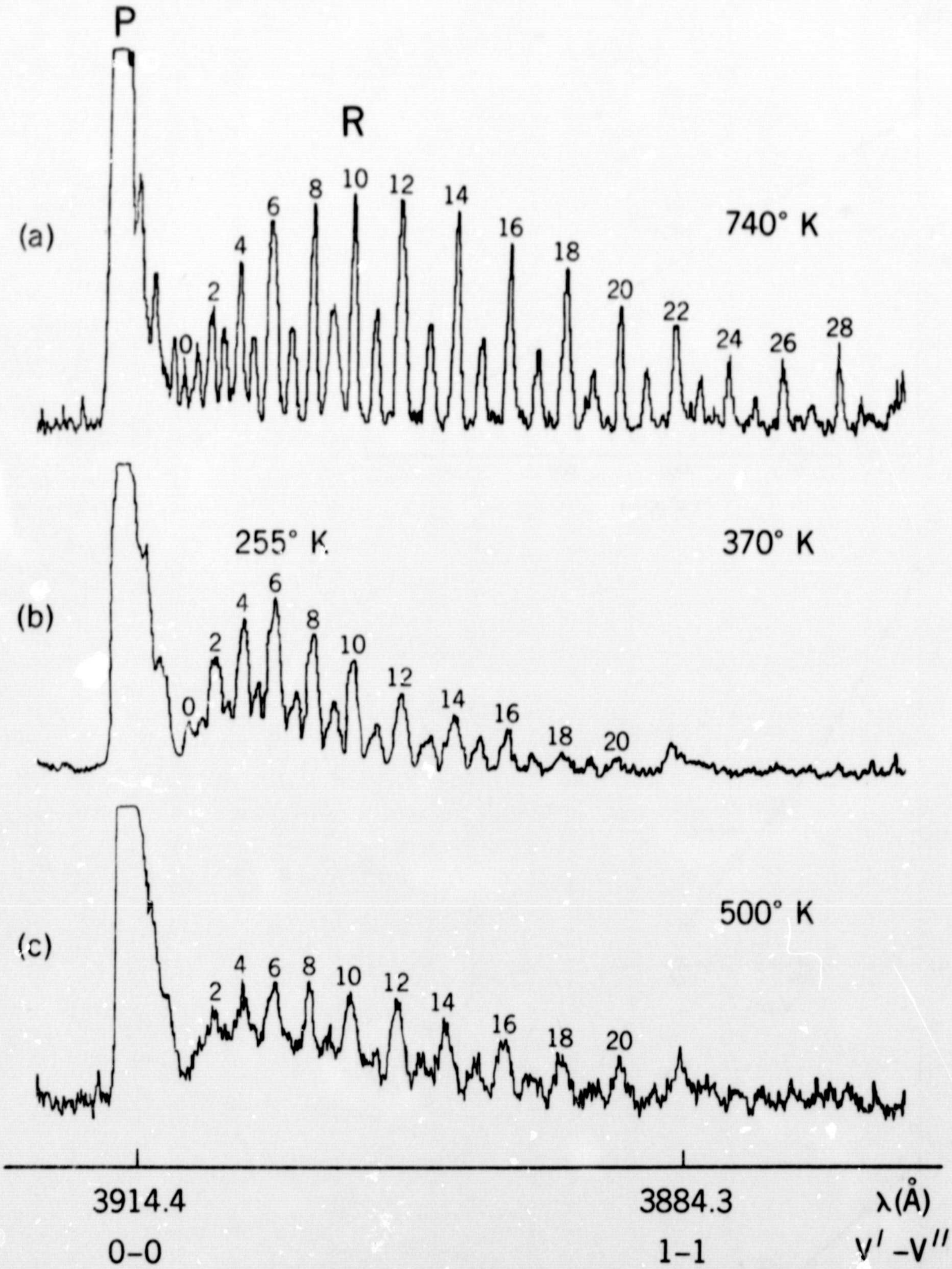

Figure 2. N_2^+ 3914Å (0-0) and 3884Å (1–1) bands. The unresolved head of the P-branch is off scale in all three spectra. a) Laboratory hollow cathode lamp. Slit width 0.1mm. T = 740°K. Maximum resolution obtainable with instrument shown in Figure 1. b) Auroral spectrum. Slit width 0.2mm. T = 255°K and 370°K. Average of 64 spectral scans. Integration time 14 minutes. c) Auroral spectrum. Slit width 0.4mm. T = 500°K. Average of 64 spectral scans with an average intensity of 3kR. Integration time 14 minutes.

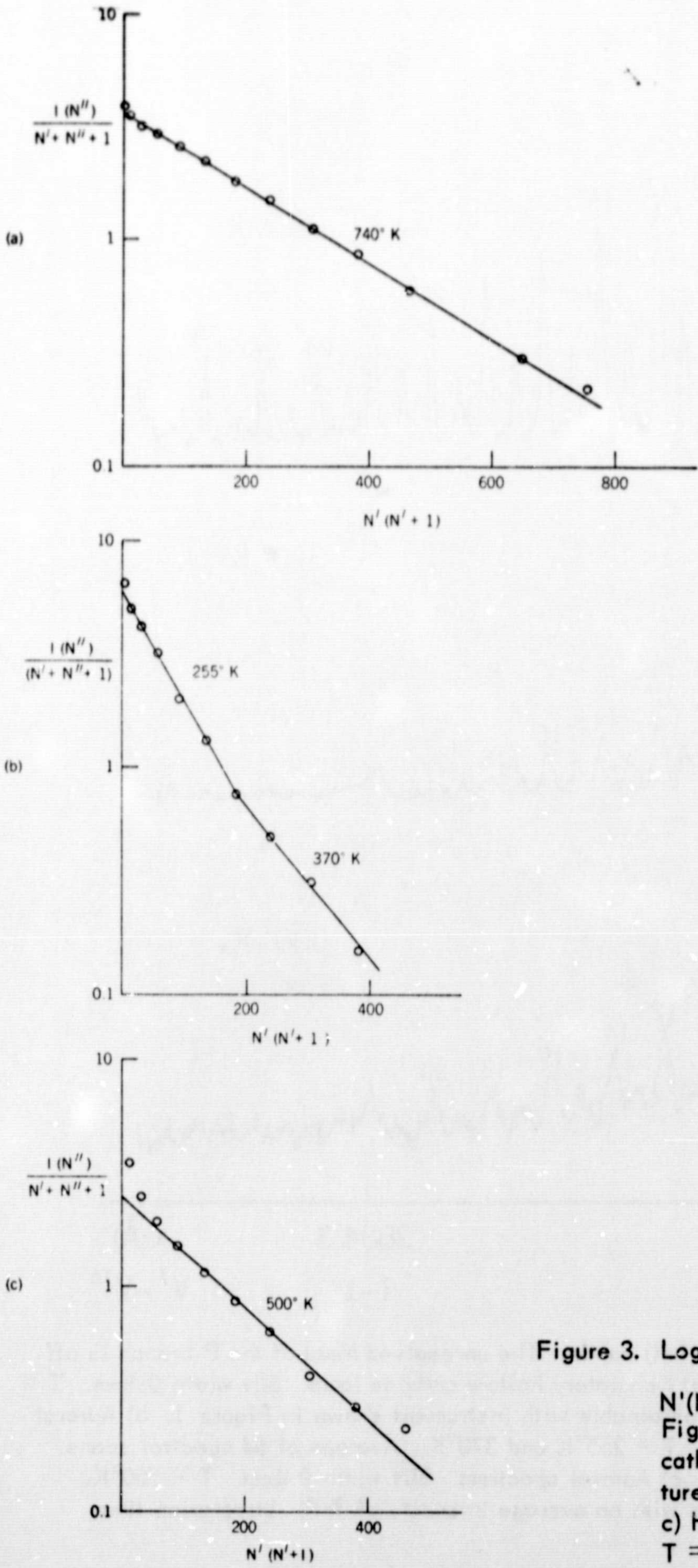

Figure 3. Log $\frac{I(N'')}{N' + N'' + 1}$ as a function of $N'(N' + 1)$ for the spectra shown in Figure 2a-c. a) Laboratory hollow cathode, T = 740°K. b) Low temperature type spectrum, T = 225°K, and 370°K. c) High temperature type spectrum, T = 500°K.