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FABRY-PEROT OBSERVATIONS OF COMET KOHOUTEK

from

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Principal Investigators

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Contents

I. Research Carried Out.

The following report, which is being prepared for submission to the Astrophysics Journal, is a full description of research completed under this grant.

Observations of Comet Kohoutek (1973f) with a Ground-Based Fabry-Perot Spectrometer

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ABSTRACT

Observations of Hα, H_2O^+, and [OI] emission lines from comet Kohoutek were made during a two month period around perihelion. Analyses of Hα line profiles and line intensities indicate that the mean outflow velocity of the hydrogen atoms was 7.8 ± 0.2 km s^{-1} and that the hydrogen atom production rate varied from about 1.0×10^{29} s^{-1} to about 3.5×10^{29} s^{-1} for comet-sun distances between 1 AU and 0.4 AU, respectively. The identification of an H_2O^+ emission feature in certain Hα scans indicates that the H_2O^+ ions were moving in a tailward direction with a velocity of 20 to 40 km s^{-1} with respect to the comet nucleus. An upper limit of 1 part in 100 was found for the D/H ratio in the cometary atomic hydrogen cloud.

Subject heading: comets

I. INTRODUCTION

Between 1973 December 1 and 1974 February 2, optical emission lines from the gas cloud surrounding Comet Kohoutek were observed using a double Fabry-Perot etalon spectrometer at Kitt Peak National Observatory. The spectrometer had a resolving power of 40,000, corresponding to a velocity resolution of about 7.5 km sec^{-1}. With this resolution it was possible to use the comet-earth relative velocity to resolve faint cometary Hα λ6563, [OI] λ6300 and other emission lines from geocoronal and airglow emissions and to study the cometary line profiles in order to obtain information about the composition, effective temperatures, outflow velocities, and production rates of atoms and ions in the cometary envelope.

II. INSTRUMENTATION

The spectrometer was coupled to the McMath Solar Telescope by focussing the primary image of the sky, which has a scale of about 1 arc min per 25 mm, directly onto the 150 mm diameter etalon of the Fabry-Perot spectrometer. Masks could readily be placed just above the Fabry-Perot to restrict the field of view from 5.7 arc minutes down to less than one arc minute as desired. The light passed by the 150 mm Fabry-Perot was coupled by a 3:1 ratio afocal lens system to a lower resolution ($\delta\lambda \simeq 1.5$Å) 50 mm Fabry-Perot which was placed in series with any one of several 50 mm aperture interference filters with bandpasses typically 15-20Å. The low resolution Fabry-Perot was used to suppress all but one of the narrow ($\delta\lambda \simeq 0.17$Å) transmission peaks of the large Fabry-Perot which fell within the passband of the interference filter. The Fabry-Perot etalons were housed in separate gas-tight chambers and pressure-scanned over spectral intervals up to 6Å using SF_6 as the scanning gas. An automatic pressure difference control system maintained the tune of the two Fabry-Perot etalons during scans. In order to monitor changes in sky brightness and atmospheric transmittance, about 4% of the light incident on the spectrometer was directed to a reference system containing a 100Å wide filter centered near the wavelength being scanned. The number of photons counted by the spectrometer and reference system during small equal wavelength scan intervals were punched on paper tape on command from an interferometric refractometer scanned in unison with the Fabry-Perot etalons. This method permitted the direct comparison and addition of scans for enhancing the signal-to-noise ratio.

III. OBSERVATIONS AND ANALYSIS

a) Cometary Hα Spectra

Cometary Hα is produced by fluorescence following solar Lβ excitation of cometary hydrogen. Examples of scans taken for the purpose of measuring cometary Hα emission are shown in figures 1 and 2. As these scans show, geocoronal Hα emission (labeled component 1) was always present and in some cases blended with the cometary emission (labeled component 2). In order to isolate the purely cometary emission features, scans of geocoronal Hα emission were taken in directions away from the comet and away from regions of expected galactic emission, thus determining the shape and position of the geocoronal components in the comet scans. The absolute wavelength calibration was obtained from the position of the geocoronal Hα line, which is fluorescently produced by solar Lβ excitation of geocoronal hydrogen. Since only the 3p levels are excited in this process, the center of gravity of the Hα line will be at 6562.74Å (Garcia and Mack 1965). In those scans were the cometary and geocoronal Hα lines were well resolved (e.g., figure 1a) the line identified as cometary Hα was always shifted in wavelength from the geocoronal line by the amount corresponding to the comet-earth relative velocity listed in the ephemeris (Clark 1973).

Useful Hα scans were taken out to 6 arc-minutes (250,000 km) from the comet head; beyond this the cometary Hα was not detectable above the noise. Figures 1b and 2b show scans taken with the field of view centered on the head of the comet. In these scans the cometary emission feature is stronger than in the sunward direction scans (figs. 1a and 2a) and also appears to have an assymetric line profile suggesting the presence of a third emission component (labeled component 3) on the red wing of the cometary Hα line. Scans taken in the tailward direction out to 200,000 km (5.5 arc-minutes) from the head (fig. 2c) in late January show this additional component more clearly. We have tentatively identified the additional line as an H_2O^+ emission line (Wehinger et al. 1974). The H_2O^+ emission was always red shifted with respect to its comet rest wavelength and was only present in the scans centered on the head and in the tailward direction. This indicates that the H_2O^+ was not expanding radially but rather was moving out in the tailward direction as would be expected for an ion. The measured tailward velocities of the H_2O^+ ions were in the range of 20 to 40 km/sec.

In the analysis of these scans, the spectra were computer fitted using three emission components convolved with the instrumental profile: 1) a geocoronal Hα line, 2) a cometary Hα line having a width determined from the unblended sunward (hence presumably H_2O^+ free) scan of 1973 December 6 and having a position relative to geocoronal Hα determined by the comet-earth relative velocity, and 3) a cometary H_2O^+ line, red shifted from cometary Hα. Except for twilight scans, the effect of the solar Fraunhofer Hα absorption line could be neglected. Reasonable variations of the parameters were allowed in the fitting routines. In the figures, the fits obtained in this manner are shown superposed on the data.

b) Absolute Hα Intensity Determination

The determination of the comet Hα intensities (photons $cm^{-2} sec^{-1} ster^{-1}$) was accomplished by two different methods. In the first method the sensitivity of the spectrometer at Hα was determined by scanning a galactic emission nebula, NGC 1499, when it was near the zenith. The Hα surface brightness of a selected region of NGC 1499 was taken as 580 ± 120 Rayleighs from a previous comparison by Reynolds (Reynolds et al. 1973) of NGC 1499 with the North

American nebula (NGC 7000) whose absolute Hα intensity was measured by Ishida and Kawajiri (1968). From several observations of the comet in a given night, the extinction for the large zenith angles (or large number of air masses) of the cometary observations was estimated, and thus comet intensities were obtained. This method is not very accurate due to the large and probably unreliable corrections for atmospheric extinction in many of the comet scans taken at large zenith angles.

The second method of obtaining absolute comet emission line intensities took advantage of the fact that geocoronal Hα was always present in the comet Hα scans. Using values of the geocoronal Hα intensities calculated from a theoretical model by R. R. Meier (1969, 1974), the comet Hα intensities were directly determined. The advantage of this method is that in each scan both comet Hα and geocoronal Hα undergo the same extinction, and thus it is not necessary to correct explicitly for extinction. Since the success of this method depends on the accuracy of the geocoronal model, the model predictions were compared with our geocoronal intensity measurements based on the NGC 1499 calibration for three scans at zenith angles less than 50° where corrections for atmospheric extinction are reliable. On two of these scans the model predictions were 14% higher than the measured intensities and on the third scan the model prediction was 15% lower than the measured intensity. The absolute Hα intensities reported here were those obtained by this geocoronal Hα comparison method.

Figure 3 shows the observed Hα surface brightnesses plotted as a function of the sun-comet distance. Since the scans were variously taken on and off the head and with different fields of view, the data were all normalized to yield the brightness averaged over a 2 arc minute field of view centered on the head at a distance of 1 AU from the earth. In doing the normalization, scans taken on the same night with different fields of view and in different positions with respect to the comet head were compared for several separate nights to estimate the Hα brightness distribution around the comet head.

c) Hydrogen Production Rates

The observed cometary Hα brightness distribution is assumed interpretable in terms of a simple radial outflow model. The method of analysis used here to determine hydrogen production rates is similar to that in Carruthers et al. (1974). The hydrogen density distribution $n_H(r')$ is given by

$$n_H(r') = Q_H/4\pi r'^2\bar{v}_H \tag{1}$$

where Q_H is the hydrogen production rate in atoms s^{-1}, r' is the distance of the hydrogen from the comet nucleus, and $\bar{v}_H$ is the average hydrogen outflow velocity. Then the column density $N_H(r)$ of hydrogen along a line of sight which has a distance r of closest approach to the nucleus is

$$N_H(r) = Q_H/4r\bar{v}_H. \tag{2}$$

The Hα intensity I_α along that same line of sight is given by

$$I_\alpha = gN_H/4\pi \tag{3}$$

where g is the number of Hα photons per second fluorescently produced by each hydrogen atom in the line of sight due to absorption of solar Lyman β photons. This approach assumes that the hydrogen cloud is optically thin to Lyman β. This assumption is justified below.

The Hα emission rate factor g is given by

$$g = g_o/R^2 \tag{4}$$

where g_o is the Hα emission rate factor at 1 AU and R is the sun-comet distance in AU. The factor g_o is given by

$$g_o = 0.12 \frac{\pi e^2}{mc} f_{31} (\pi F_o) \tag{5}$$

where the factor 0.12 is the Hα branching ratio from the 3p state, $\frac{\pi e^2}{mc} f_{31}$

is the scattering coefficient for Lyman β, and πF_0 is the solar Lyman β photon flux per unit frequency interval at 1 AU in the neighborhood of the cometary Lyman β line.

The profile of the solar Lβ emission line integrated over the solar disk has not been measured. The Lβ profile measured at one point on the sun by Tousey (1962) shows a self-reversed line with a peak to valley ratio of 3 to 1. Geocoronal hydrogen would be excited by solar Lβ in the valley of this profile, while the comet-sun velocity during our observations Doppler-shifted the cometary hydrogen Lβ line to a peak of the solar Lβ profile. The g_0 factor which accounts for the geocoronal emission is 1.5×10^{-5} s^{-1} (Meier 1974); thus the g_0 factor for cometary hydrogen is taken to be 4.5×10^{-5} s^{-1} under the assumption that the Tousey profile is a reasonable approximation to the integrated disc profile.

The hydrogen atom mean outflow velocity $\overline{v}_H$ was determined from the observed line profiles, which had a width about two times instrumental width. The profiles cannot be fitted by assuming that the comet hydrogen atoms were all moving with the same speed. However, reasonable fits are obtained assuming that all the H atoms were moving radially outward with a speed distribution that was Maxwellian (Bertaux et al. 1973). With this model we obtain a mean outflow velocity $\overline{v}_H$ of 7.8 ± 0.2 km s^{-1} (which corresponds to a temperature of 2900 ± 150°K).

In a radial outflow model for the comet, the average brightness over the field of view is approximately the brightness at the center of the field of view if the comet head is not in the field. Analysis of the sunward scan in figure 1a (used as an example throughout this section) gives a maximum hydrogen density of $1.0 \pm 0.2 \times 10^3$ cm^{-3} at the center of the field of view (84,000 km from the comet center). This corresponds to a production rate $Q_H = 3.5 \pm 0.6 \times 10^{29}$ hydrogen atoms s^{-1} for a comet-sun distance of 0.75 AU.

The effect of multiple scattering of Lβ was estimated by considering a thermalized 2900°K hydrogen cloud with a density falling as $1/r'^2$ from the comet head and having a density of $10^3 cm^{-3}$ at $r' = 8.4 \times 10^4$ km. Under these conditions it is readily shown that the solar Lβ flux would be reduced by 1/e at a distance of 5.4×10^3 km from the comet head. Since the region within this radius would contain less than 10% of the total number of hydrogen atoms in the 2 arc minute field of view, we neglected multiple scattering of solar Lβ.

The accuracy of the simple radial outflow model used here is limited by at least two effects (Carruthers et al. 1974). First, solar Lα radiation pressure would tend to push the hydrogen cloud away from the sun. For the outflow velocity of 7.8 km s^{-1} found from the scan shown in figure 1a, one finds that the hydrogen atoms took about 10^4 seconds to move from the comet head to distances corresponding to the center of the field of view. Radiation pressure would have slowed these atoms by only 0.07 km sec^{-1}, and thus would have had little effect on results deduced from this scan. The error in neglecting this effect is less than 5% of the Hα surface brightnesses determined from any of our scans. A second effect is the finite lifetime of the hydrogen cloud due to ionization by the solar wind. Carruthers et al. (1974) give a lifetime of about 2×10^6 sec for the comet-sun distance for figure 1a, which means that the hydrogen atoms on the average passed well beyond the region explored in this study before the effects of ionization were significant. The error in neglecting this effect on the surface brightness is less than 5% for any of our scans.

Figure 4 shows the hydrogen atom production rates plotted versus the comet-sun distance. Scans centered off the comet head were used to determine the absolute production rate in the manner indicated above. A direct determination of the production rate from head-centered scans would require a model for hydrogen densities near the nucleus. To avoid this problem, only relative production rates were determined from the head-centered scans, and these in turn were normalized to the production rates determined from scans off the head on those days in which scans both on and off the head were made.

d) Deuterium/Hydrogen Ratio

In an attempt to measure the D/H ratio, several scans were extended to include the region 1.8 Å to the blue of Hα which is the expected position of the Dα emission line. Figure 5 shows preperihelion and postperihelion scans. Before perihelion the comet-sun velocity Doppler shifted the cometary hydrogen Lβ line to the red peak (assuming the Tousey profile) of the solar Lβ line and the cometary deuterium Lβ line to the blue peak of the solar Lβ line. After perihelion the solar spectrum was red shifted relative to the comet, placing the cometary hydrogen Lβ line on the blue peak of the solar Lβ line and the cometary deuterium Lβ line completely off the solar Lβ line. Thus postperihelion observations should show no Dα feature. In preperihelion observations cometary deuterium and hydrogen would have approximately the same g factor and therefore a direct D/H ratio could be measured if the Dα line were detected.

Scans for Dα were taken to within 10 days of perihelion. The spectrum is complicated by two terrestrial H_2O absorption features, a weak cometary H_2O^+ line and possibly other weak airglow or cometary features. In the near-perihelion period the comet was visible only in the morning twilight sky where terrestrial features were enhanced. Ten days before perihelion the morning twilight dominated even the cometary Hα emission and measurements were halted. After perihelion, observations in the Dα region of the comet spectrum were made for comparison. Observations of the morning twilight were also made to remove terrestrial features. An analysis of all Dα scans did not show any significant additional feature on the preperihelion scans that could be attributed to cometary Dα emission. Based on the noise in the Dα region we are able to put an upper limit of 1 part in 100 for the D/H ratio in the cometary atomic hydrogen cloud.

e) [OI] λ6300 Å Emission

By changing the interference filter and retuning the etalons, observations could also be made at 6300 Å in order to observe [OI] emission from the comet. By comparing filter efficiencies, etalon transmission curves and photomultiplier quantum efficiencies, the instrument efficiency at 6300 Å relative to the efficiency at Hα could be determined, permitting absolute intensity measurements. Atmospheric extinction estimates were made by comparing several scans made on the same day, as in the first method described above for Hα.

All 6300 Å scans, examples of which are shown in figure 6, contain the [OI] airglow feature at 6300.23 Å (Chamberlain 1961). The measured airglow surface brightness indicates that the calibration was reasonable; however it is not sufficiently well known to use for calibration. Scans on and near the comet head show an additional line shifted from the airglow line by the Doppler shift corresponding to the comet-earth relative velocity, and is identified as cometary [OI] λ6300 emission. This cometary [OI] emission presumably is produced by molecular dissociations which leave the oxygen atoms in the ^1D state. Collisional de-excitation occurs only in a very small region near the center of the comet, and both fluorescence and collisional excitation must be small (Arpigny 1965, Biermann and Trefftz 1964).

The cometary line was consistently slightly wider than the airglow line, but the uncertainty in the derived width is large because the width was approximately one half the instrumental width, which was chosen to be optimum for the hydrogen measurements. The measured full width at half maximum of the cometary [OI] profile was 2.7 (+1.0, -1.3) km s^{-1} (corresponding to an effective temperature of 2400 [+2200, -1800]°K). These velocities are insufficient to carry the excited atoms outside the field of view before radiating. Therefore, the absolute intensity measurements of [OI] λ6300 give directly the production rate of oxygen atoms in the ^1D state. The surface brightness of 200 ± 100 Rayleighs measured on 1973 December 8 gives a ^1D oxygen production rate of $2 \pm 1 \times 10^{28}$ s^{-1}. The ^1D oxygen production rates have been plotted as a function of comet-sun distance in figure 7.

IV. DISCUSSION

The values we have obtained for the hydrogen production rate at various heliocentric distances, shown in figure 4, are generally in good agreement with the results obtained by Carruthers et al. (1974) using Lyman alpha imagery of Comet Kohoutek. At present, the major source of uncertainty in our results for hydrogen is probably the lack of reliable solar Lyman beta profiles, integrated over the solar disk, for different levels of solar activity. Presumably, such observations will eventually be carried out.

Additional analysis of the red shifted H_2O^+ emission line detected in our Hα scans is being carried out in order to obtain an estimate of the H_2O^+ production rate in Comet Kohoutek. It should then also be possible to obtain an estimate of the H_2O production rate, using the relevant cross-sections for photodissociation and photoionization of H_2O.

Since a number of different molecules, including H_2O, could be sources of the hydrogen and ^1D oxygen atoms which produced the emissions we observed, we cannot at present use our observations to determine the production rate of oxygen or any of the possible parent molecules. However, the ^1D oxygen production rates at least set a lower limit to the total oxygen production rate, and thus our results are consistent with the observations of Feldman et al. (1974) who found a production rate of 1.4×10^{29} s^{-1} for oxygen. These rates indicate that about 14% of the oxygen atoms were produced directly into singlet states.

In conclusion, we feel that ground-based Fabry-Perot observations of comets can provide a powerful tool for the study of comets, especially when carried out in close coordination with other types of observing techniques.

We would like to thank F. Barmore and B. Donn for their assistance and advice. We are especially grateful to R. R. Meier for calculating the geocoronal Hα intensities used in our cometary Hα intensity determinations. This work was carried out with support from Kitt Peak National Observatory, the University of Wisconsin Graduate School, the Planetary Astronomy Program of the National Aeronautics and Space Administration through grant NGR 50-002-242, and the Aeronomy section of the National Science Foundation through grant GA-40146.

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FIGURE CAPTIONS

Fig. 1 Spectral scans near Hα taken on 1973 December 6 with a circular 2 arc-minute field of view. Scan (a) was taken at 1250 UT with the center of the field 1.5 arc-minutes (84,000 km) sunward of the comet head. The geocoronal Hα line (component 1) is at 6562.74 Å, and the cometary Hα line (component 2) is blue shifted 0.63 Å corresponding to the comet-earth relative velocity. The continuous line through the data is generated by a continuum and a two-Gaussian fit, the components of which are shown below the data. Scan (b) was taken at 1235 UT centered on the head. A third emission feature is evident, and the fit shown includes a third Gaussian component (component 3) 0.3 Å redward of cometary Hα. Scan (c) was taken at 1300 UT with the field of view centered 1.5 arc-minutes tailward of the comet head. The fit again includes a third component red-shifted by 0.3 Å from cometary Hα, and identified as H_2O^+.

Fig. 2 Spectral scans near Hα taken 1974 January 26 with a circular 6 arc-minute field of view. Scan (a) is the sum of scans taken at 0254 UT and 0428 UT and centered 5.5 arc-minutes (2.1×10^5 km) sunward of the comet head. The cometary Hα line (component 1) is red-shifted from the geocoronal Hα line (component 2) at 6562.74 Å due to the comet-earth relative velocity. Scan (b), taken at 0350 UT centered on the comet head shows the H_2O^+ feature (component 3). Scan (c) is the sum of scans taken at 0307 UT and 0416 UT with the field centered 5.5 arc minutes tailward of the comet head. The third component is again evident.

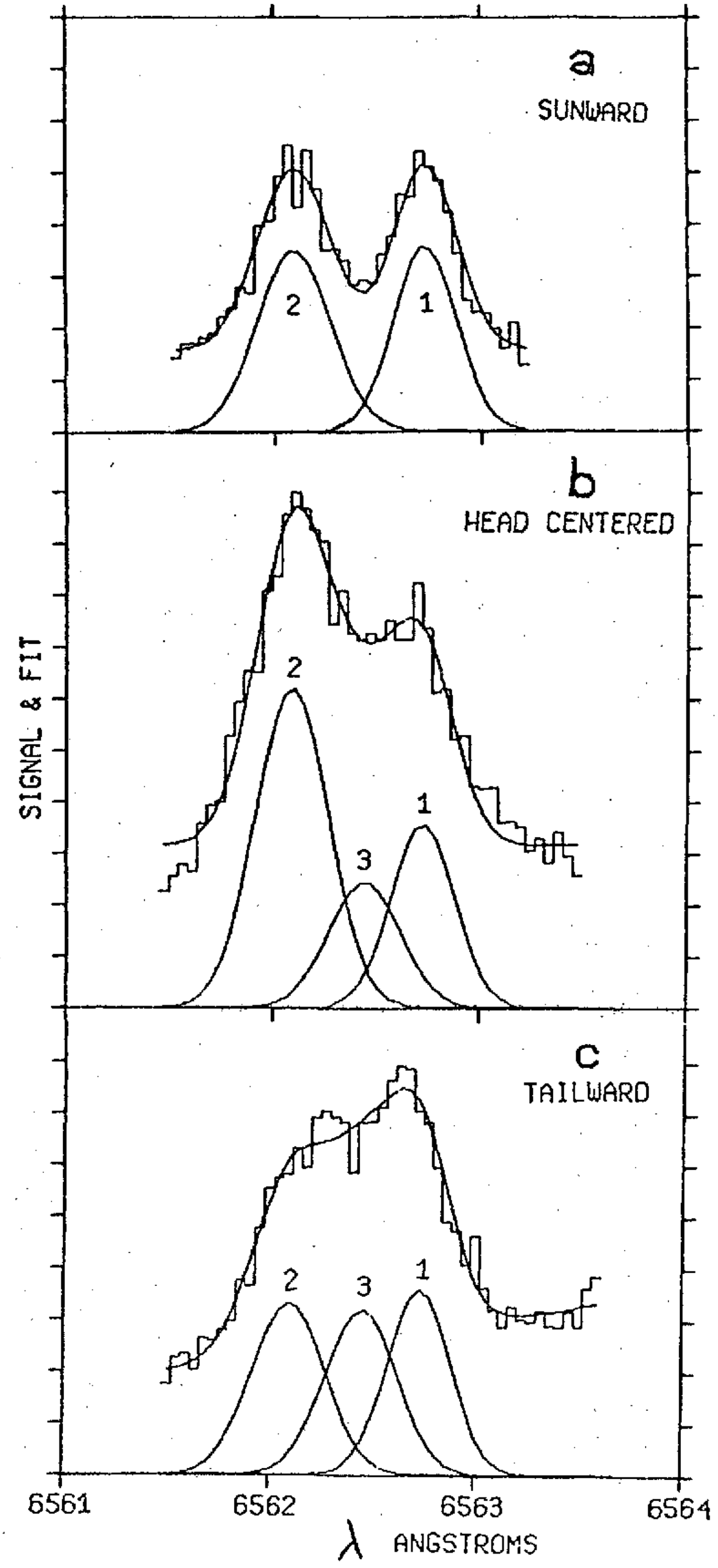
Fig. 3 Brightness of cometary Hα emission. The ordinate gives the brightness averaged over a 2 arc-minute head-centered field at a distance of 1 AU from the earth as a function of the comet-sun distance. Preperihelion data are shown as open circles and postperihelion data are shown as closed circles.

Fig. 4 Hydrogen atom production rate as a function of the comet-sun distance.

Fig. 5 Comparison of preperihelion and postperihelion scans near Hα, including the region where Dα emission would occur. Positions marked are (from left to right): unidentified terrestrial airglow emission, cometary H_2O^+ emission, cometary Dα emission, terrestrial H_2O absorption, cometary Hα emission, and geocoronal Hα emission.

Fig. 6 Spectral scans taken near [OI] λ6300 Å on 1974 January 24 with a circular 40 arc-second field of view. Scan (a) was taken at 0230 UT centered on the comet head, and shows the cometary [OI] λ6300 Å emission red-shifted due to the comet-earth Doppler shift by 0.45 Å from the [OI] airglow feature at 6300.23 Å. Scan (b) shows the same spectral region scanned at 0240 UT with the field of view centered 40 arc-seconds (24,000 km) off the comet head. Scan (c) is the sum of two scans taken at 0205 UT and 0250 UT with the field centered 80 arc-seconds off the comet head.

Fig. 7 Production rate of ^1D oxygen atoms as a function of the comet-sun distance.


a
SUNWARD
2
1
b
HEAD CENTERED
2
3
1
c
TAILWARD
2
3
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SIGNAL & FIT
6561
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6563
6564
λ ANGSTROMS

FIGURE 1

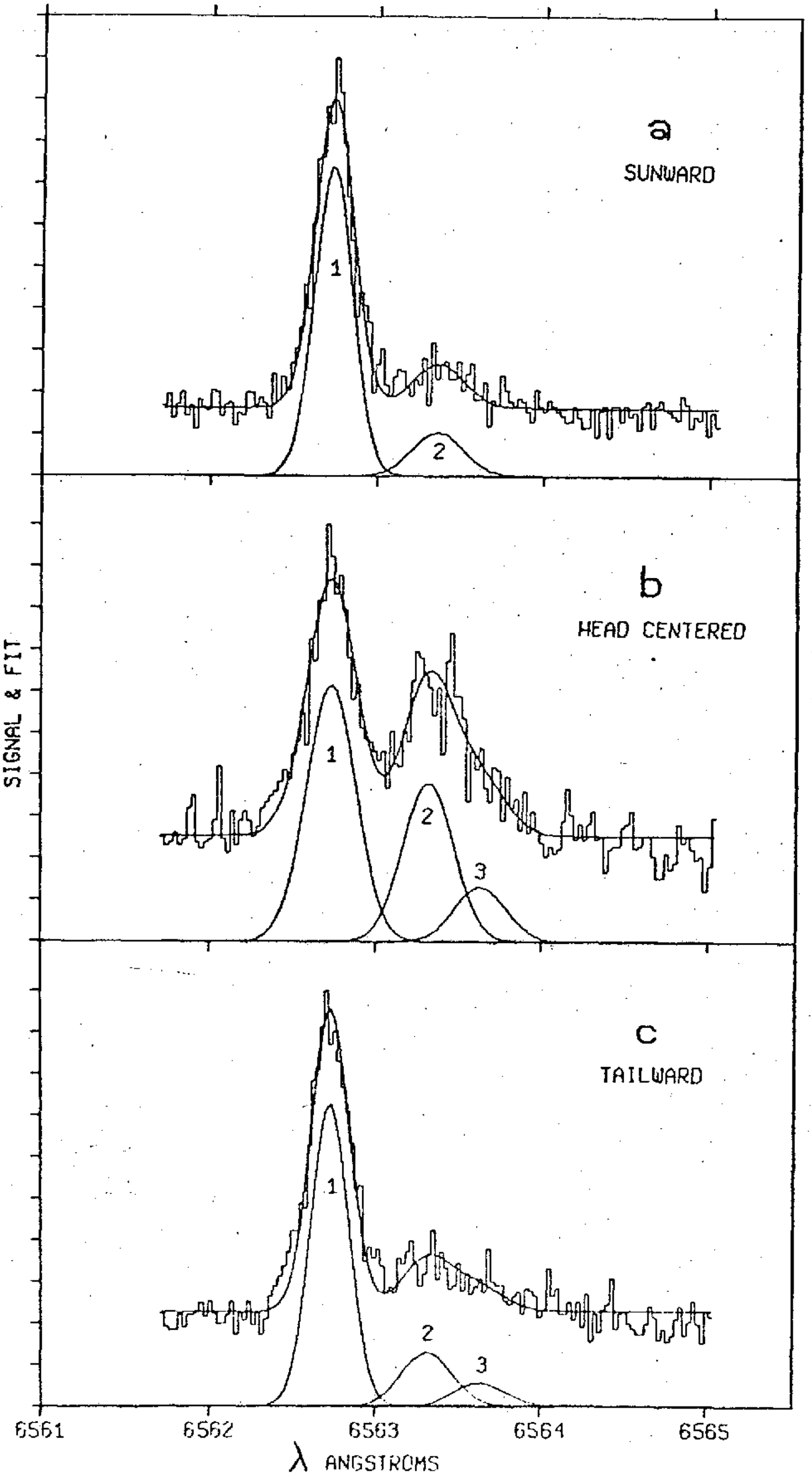
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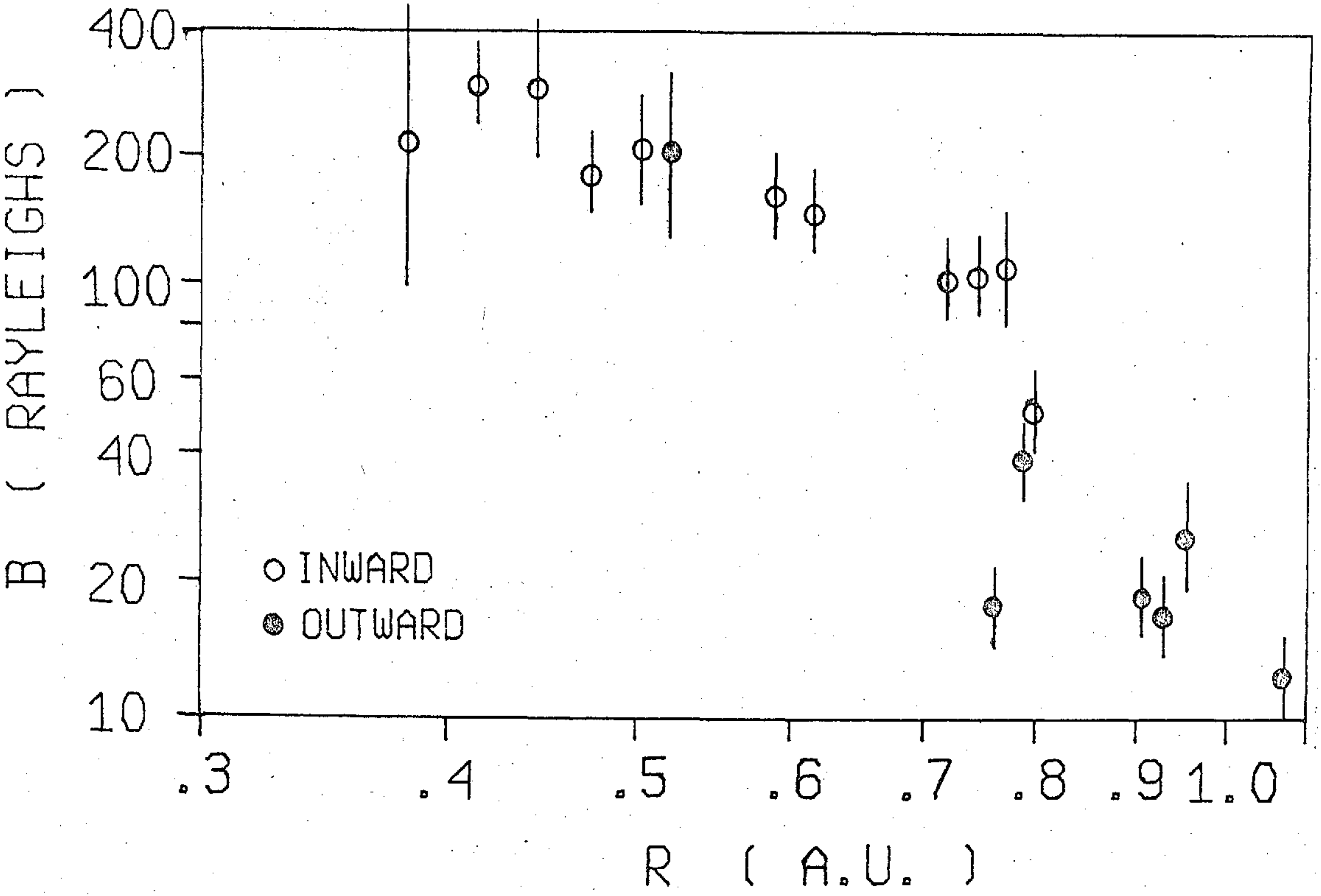
FIGURE 2


400
200
100
60
40
20
10
B (RAYLEIGHS)
○ INWARD
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R (A.U.)

FIGURE 3

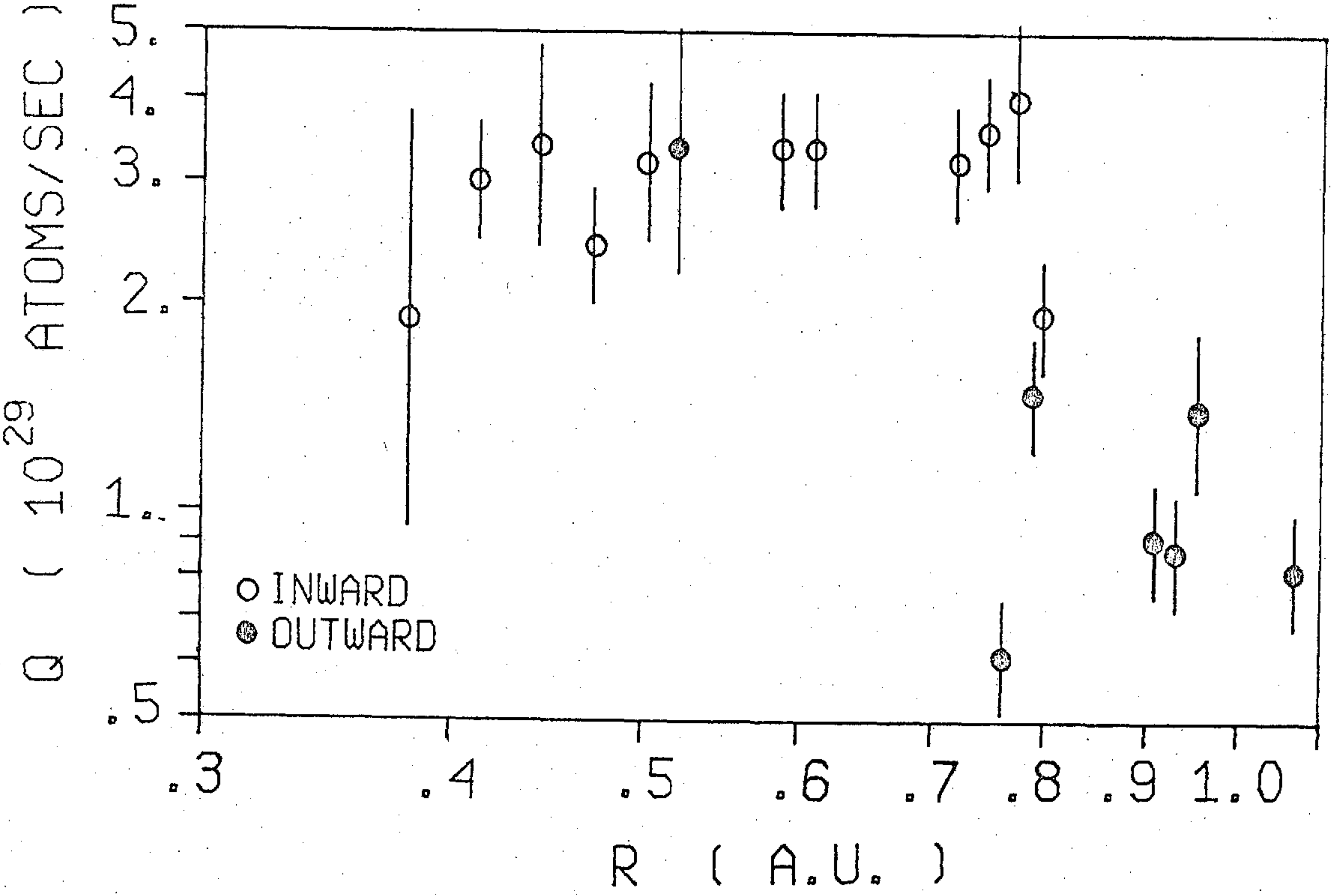
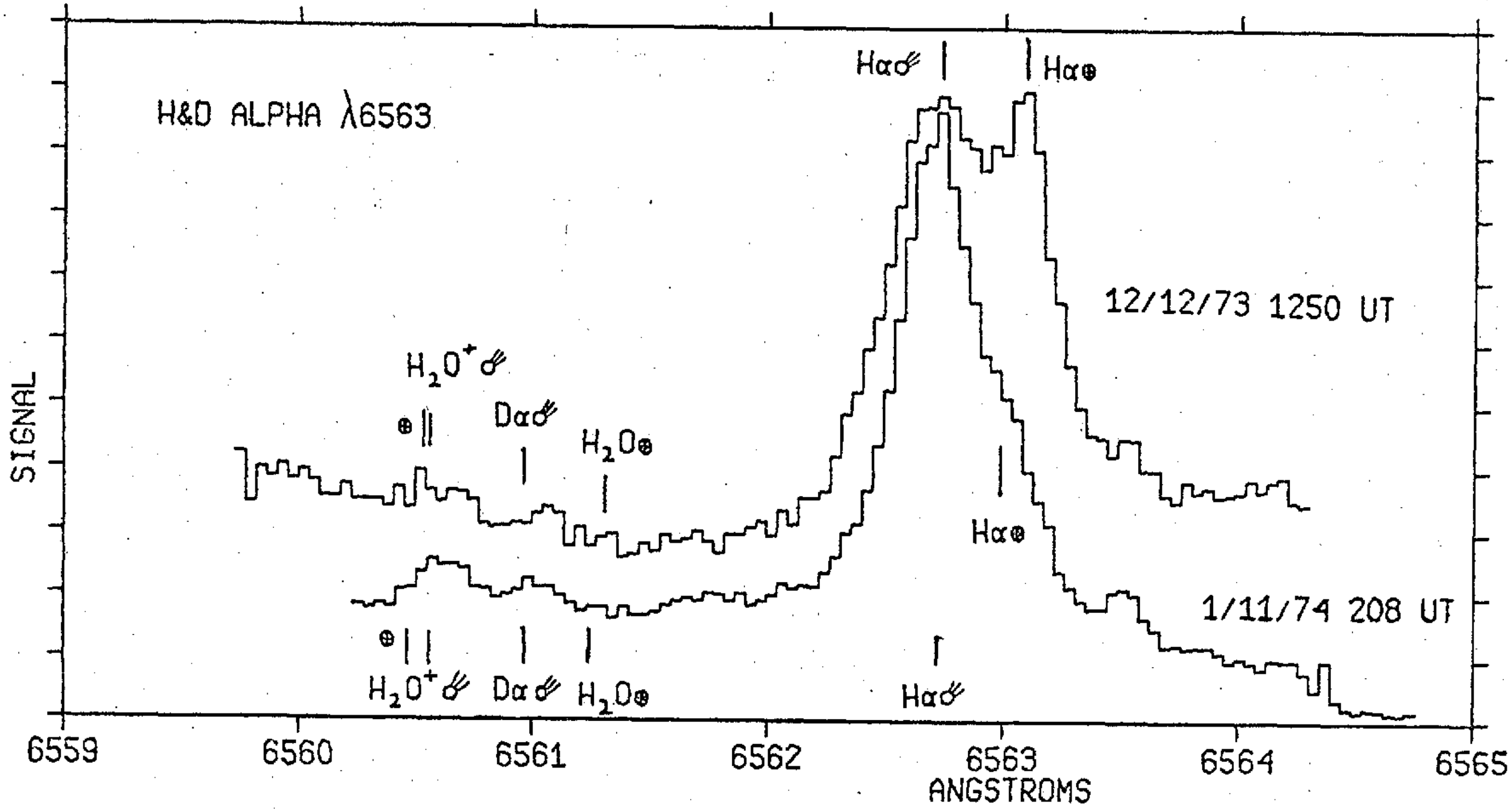


FIGURE 4


H&D ALPHA λ6563
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⊕
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Hα⊕
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ANGSTROMS

FIGURE 5

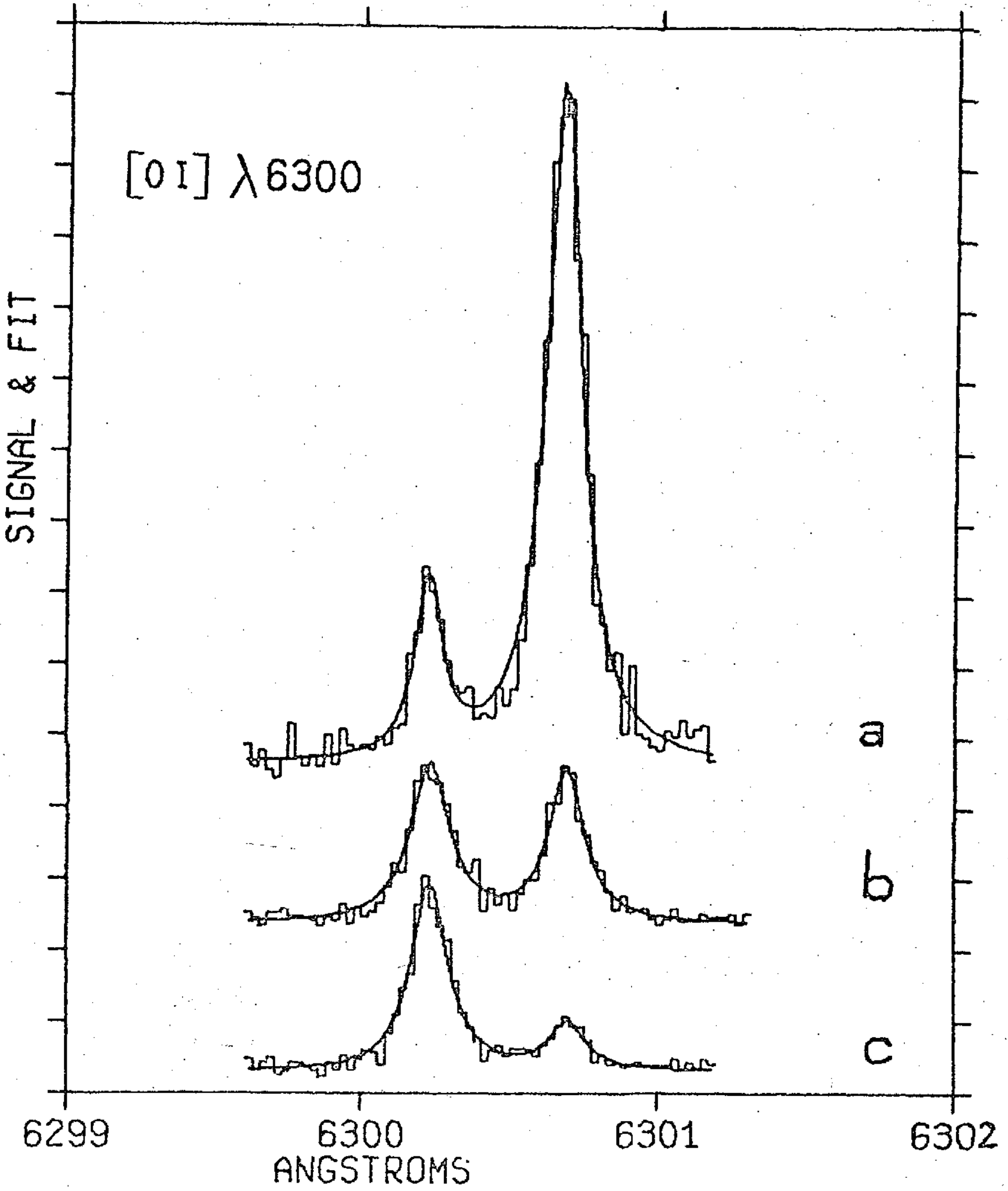

FIGURE 6

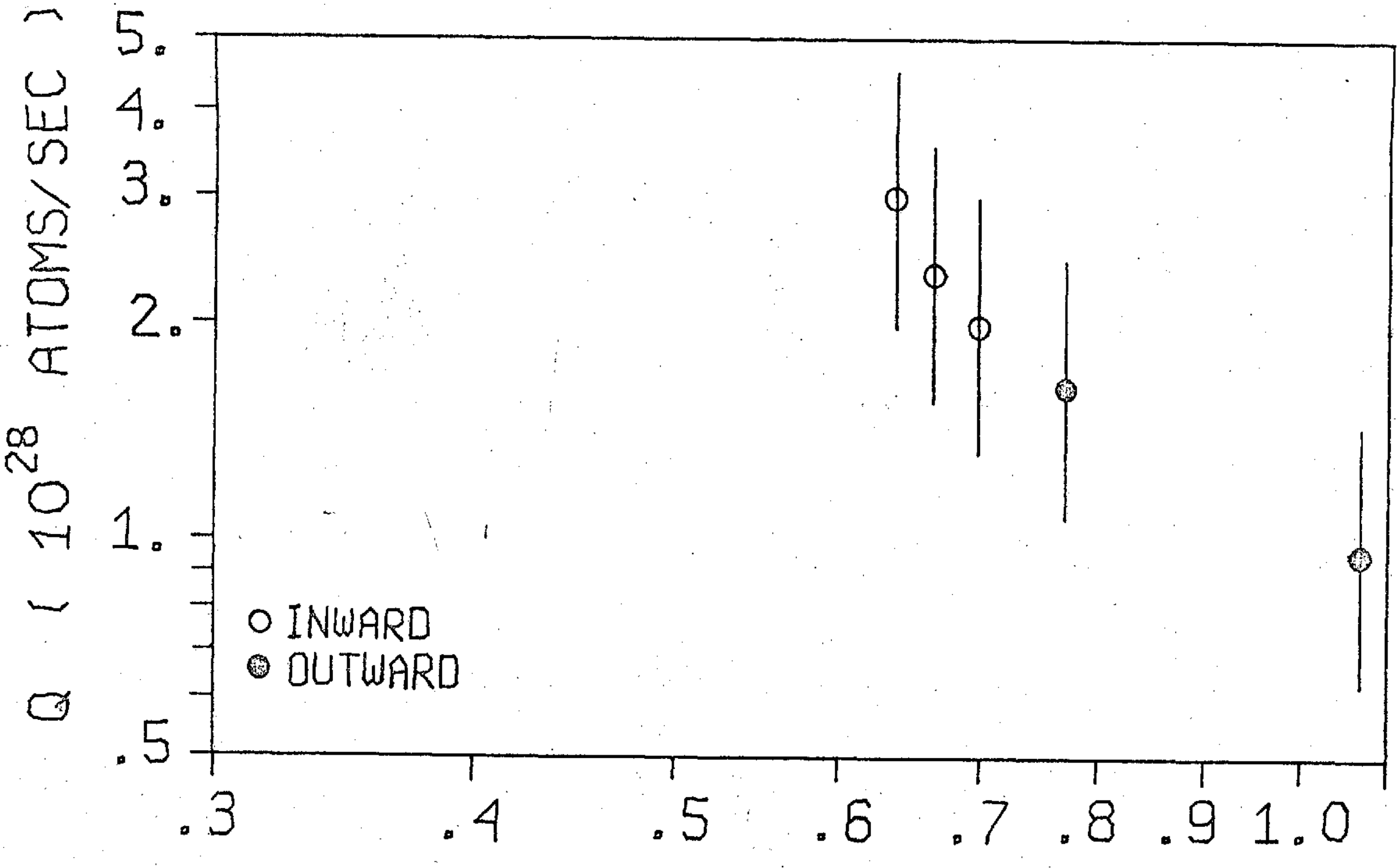

FIGURE 7

II. Personnel.

A. The following persons received support from this grant:

1) Frank E. Barmore
2) John T. Trauger

B. The following persons participated in the research without direct support from this grant.

1) D. H. Huppler
2) F. L. Roesler
3) F. Scherb
4) R. J. Reynolds

III. Conference Reports

1) Fabry-Perot Observations of Hydrogen and Oxygen on Comet Kohoutek (1973f). J. Trauger et al.. American Astronomical Society, April 1974.

2) Ground Based Fabry-Perot Observations of Atomic Hydrogen and Oxygen in Comet Kohoutek, D. H. Huppler et al.. American Geophysical Union, April 1974.

3) Ground Based Fabry-Perot Observations of Comet Kohoutek. D. H. Huppler et al., Comet Kohoutek Workshop, Marshall Space Flight Center, Alabama, June 13, 1974.

4) Observations of Comet Kohoutek, F. L. Roesler et al., University of Wisconsin Physics Dept. Colloquium, May 3, 1974.