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Rocket and spacecraft studies of ultraviolet emissions from astrophysical targets

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Far-ultraviolet spectral measurements from rockets and spacecraft of a number of astrophysical targets are described.

Rocket studies of Arcturus (α Boo) in 1969 provided the first observation of ground state atomic hydrogen and atomic oxygen emissions from the chromosphere of a cool star other than the Sun. More recent rocket measurements show the presence of atomic oxygen (1304 Å) emissions and the absence of atomic carbon (1560 and 1657 Å). New studies of this star with the Copernicus satellite have provided detailed information about the spectral shape of H Ly α and Mg II 2800 Å radiation. Far u.v. spectra of the planets Venus and Jupiter were also obtained during our rocket experiments.

Precision photometric measurements of emissions from several bright stars were obtained with the far u.v. spectrometer aboard the Apollo 17 spacecraft. The u.v. background was also observed by the Apollo 17 spectrometer.

Apollo 17 u.v. observations showed that solar protons do not produce an atomic hydrogen atmosphere on the Moon. The alternative H_2 formation would not have been detectable.

Rocket studies of Comet Kohoutek on 5.1 January 1974 U.T. showed a large atomic hydrogen cloud (Ly α 1216 Å), atomic oxygen (1304 Å), atomic carbon (1560 and 1657 Å) and OH (3090 and 3142 Å).

1. Introduction

About 37 years ago I [W. G. F.] had the good fortune to attend R. W. Wood's final lecture demonstration course in physical optics at The Johns Hopkins University. About 37 years before that R. W. Wood first came to London and began his long friendship with Lord Rayleigh and with the Royal Society. I mention these facts to make it clear how much I treasure the opportunity to address this Society and to suggest that the fact that there is a current group of spectroscopists and astronomers at the Johns Hopkins University is a matter of heritage rather than coincidence. More generally perhaps the genius of men like Rayleigh and Wood is as important an influence on today's research as is our current spectacular technology.

Our space experiments began in 1959 and were restricted to spectrometric studies of upper atmospheric emissions until 1965 when we attempted to observe the far u.v. spectrum of Comet Ikeya Seki. The experiment failed because of direct solar radiation scattered by the telescope, but our appetite for astrophysical observations was whetted, inspiring a series of experiments described below, the latest of which was the successful observation this year of Comet Kohoutek (1973f). Our choice of astrophysical targets has been made less with the mentality of astronomers than with the instincts of a Mississippi River boat gambler.

2. Cool stars

We first observed Ly α emissions from Arcturus (α Boötes) with a 1970 rocket experiment (Rottman, Moos, Barry & Henry 1971). More detailed spectra (Moos & Rottman 1972) were obtained with a LiF prism spectrometer (Moos, Vitz, Barry & Buckley 1970) with its entrance slit at the focus of a high resolution, precision pointed rocket telescope (Bottema, Fastie & Moos 1969). Figure 1 shows the rocket spectrum compared to the earth airglow spectrum obtained on the same flight and with a synthetic solar spectrum (less continuum background) for comparison. These spectra clearly show that α Boötes has a chromosphere, revealed by neutral atomic hydrogen and neutral atomic oxygen lines, and has a neutral atomic carbon line much weaker than in the solar case. The observed signals indicate that the surface brightness of α Boötes is somewhat less than that of the Sun at 1216 Å (Ly α).

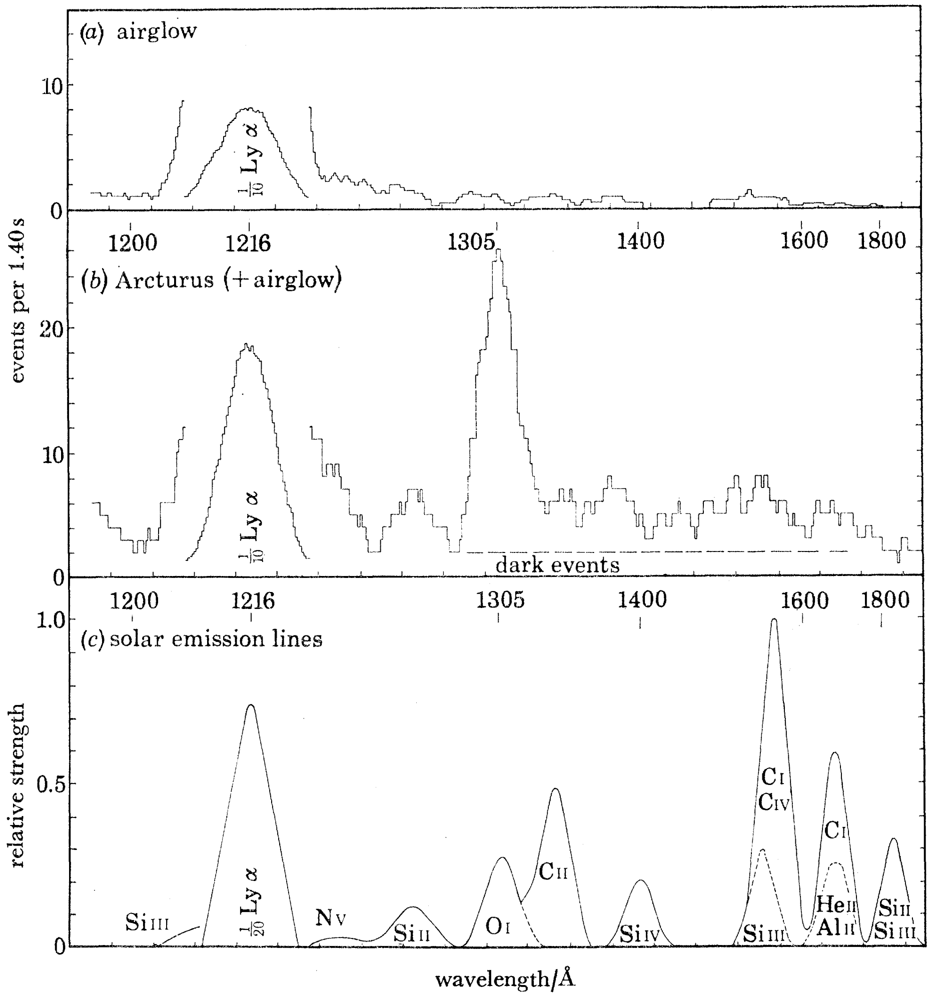

Figure 1. Rocket spectrometer spectrum of α Boo compared to night airglow and synthetic solar spectrum less solar continuum.

There are indications of other emission features in the 1350–1600 Å range. Further studies of this radiation are in progress.

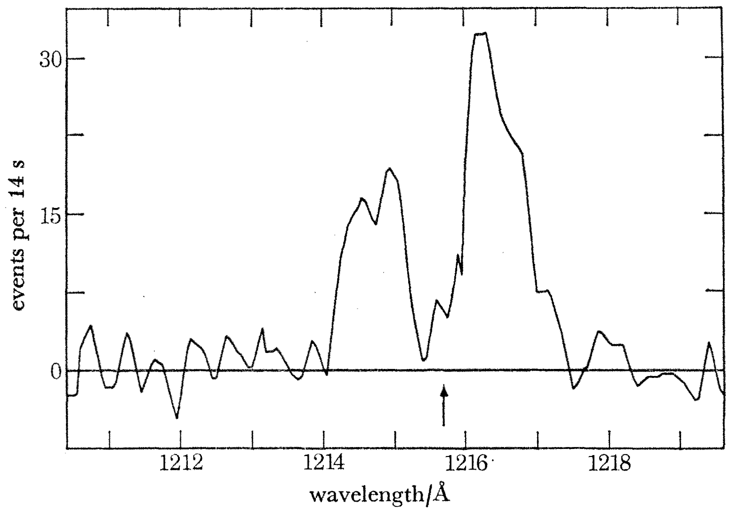

Figure 2. High resolution spectrum of Lyman α emission from α Boo obtained with the Copernicus satellite.

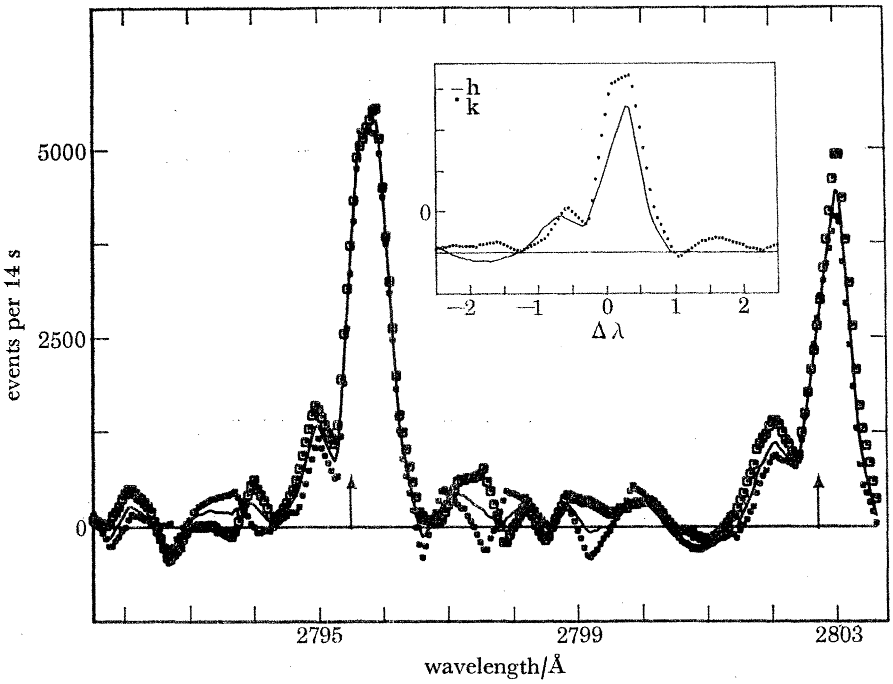

Figure 3. High resolution spectrum of magnesium emission lines of α Boo obtained with the Copernicus satellite.

We have studied spectral details of the Ly α 1216 Å emission using the Princeton OAO high resolution spectrometer (Moos, Linsky, Henry & McClintock 1974). As shown in figure 2, the Ly α line is much broader than the solar Ly α emission line and is unsymmetrically reversed. Figure 3 shows the Mg II doublet at 2795 and 2803 Å which was obtained by OAO III and which is also unsymmetrically reversed. These line reversals have been interpreted as evidence for neutral and ion stellar winds (Moos *et al.* 1974).

3. ABSOLUTE U.V. BRIGHTNESS OF B STARS

The Apollo 17 spacecraft carried a large far ultraviolet Ebert spectrometer (Fastie 1973) whose prime purpose was to study the lunar atmosphere (Fastie *et al.* 1973). No external optics were employed with this instrument which was absolutely calibrated with great care, probably to ± 10 %. The fact that all optical elements were internal, that pulse counting photomultiplier circuitry was employed to decrease the influence of the photomultiplier tube gain, that the instrument sensitivity was monitored during the mission by repeated observations in lunar orbit of the lunar albedo and in transearth coast by almost continuous observations of the solar system Ly α emission, and that the absolute sensitivity is comparable to National Bureau of Standards photometric measurements provides spectral flux measurements of high reliability. Because no external optics were employed and the diffraction grating subtended a 144 square degree field of view, only a few bright, well isolated stars were observable.

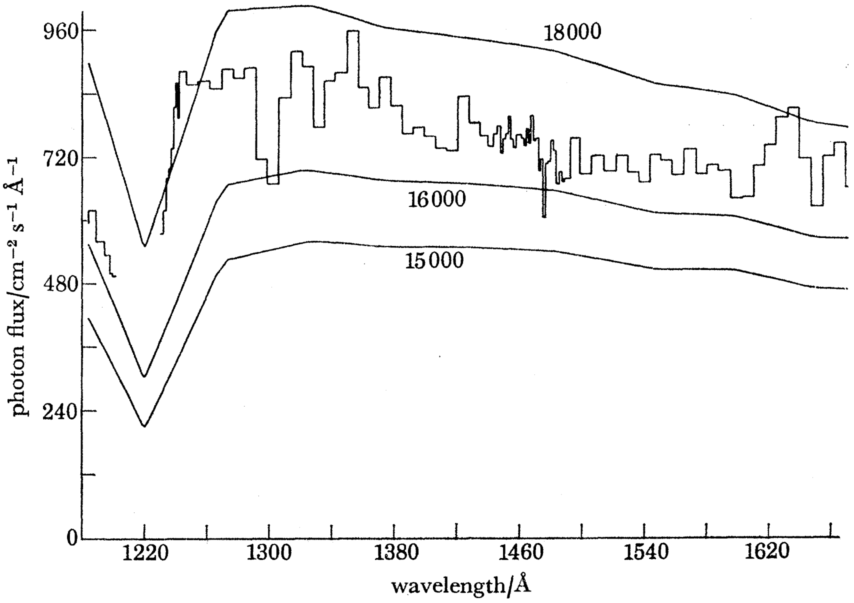

FIGURE 4. Spectrum of η Ursae Majoris obtained by Apollo 17 far u.v. spectrometer.

Figure 4 shows the spectrum we obtained for η Ursae Majoris compared to the model of Kurucz, Peytremann & Avrett (1972) for three different effective temperatures. A reddening correction ($E_{B\text{-}V} = 0.02$) has been applied to the theoretical curves which are averages over a 50 Å interval. The ultraviolet reddening correction is according to Bless & Savage (1972).

Our measurements short of 1200 Å from Apollo 17 and our earlier rocket measurements below 1200 Å with a prism spectrometer (Opal *et al.* 1968) lie below the model for η Ursae Majoris. However, systematic calibration errors in this region may be larger than expected.

Table 1 summarizes the measurements at 1450 Å from six stars observed by the Apollo 17 spectrometer and compares our results with our earlier rocket observations (Opal *et al.* 1968), with observations of Bless, Fairchild & Code (1972) and Smith (1967). For further comparison we show the models of Kurucz *et al.* (1972) for various effective temperatures. Considering the absolute calibration difficulties in this spectral region, the intercomparison of experimental

TABLE 1. EXPERIMENTAL AND THEORETICAL FAR U.V. STELLAR FLUXES

				10^3 photons $\text{cm}^{-2}\,\text{s}^{-1}\,\text{Å}^{-1}$ at 1450 Å					
								Kurucz *et al.* model	
star	V	$(B\text{-}V)_0$	$E_{B\text{-}V}$	Apollo 17	Opal *et al.*	Bless *et al.*	Smith (1376 Å)	reddened flux	T_e
ζ Oph	2.56	−0.30	0.32	0.29–0.44	—	—	0.24	0.37	35000
α Vir	0.96	−0.26	0.02	3.03–3.5	—	—	2.95	4.72	25000
ζ Tau	2.99	−0.24	0.06	0.28–0.42	—	—	0.22	0.36	20000
η U Ma	1.86	−0.20	0.02	0.68–0.83	0.60	0.97	0.66	0.92	18000
α Eri	0.47	−0.16	0.00	1.9–2.3	—	—	1.31	2.11	15000
α Gru	1.73	−0.16	0.02	0.35–0.53	—	—	—	0.61	15000

results is encouraging and indicates that the model prediction for the given effective temperature is generally high.

It appears from these results that as far u.v. photometric standards and calibration techniques improve absolute stellar brightness measurements will compete in accuracy with ground-based measurements in the visible region. Extension of the far u.v. absolute brightness measurements to more distant stars and to cooler stars can also be anticipated.

4. Planetary observations

Our rocket studies of stellar emissions were coordinated with far ultraviolet studies of planetary spectra. Figure 5 shows the spectrum of Venus (Rottman & Moos 1973). The Ly α signal is smaller than had been reported by the Mariner 5 photometer (Barth *et al.* 1967), according to Wallace (1969). The OI feature at 1304 Å was unpredicted. The 1560 and 1657 Å features represent C I emissions and the remaining radiation in the region 1400–1700 Å is due predominantly to the CO 4th positive system. These observations have been recently confirmed by the spectrometric measurements of Mariner 10 (Broadfoot, Kumar, Belton & McElroy 1974).

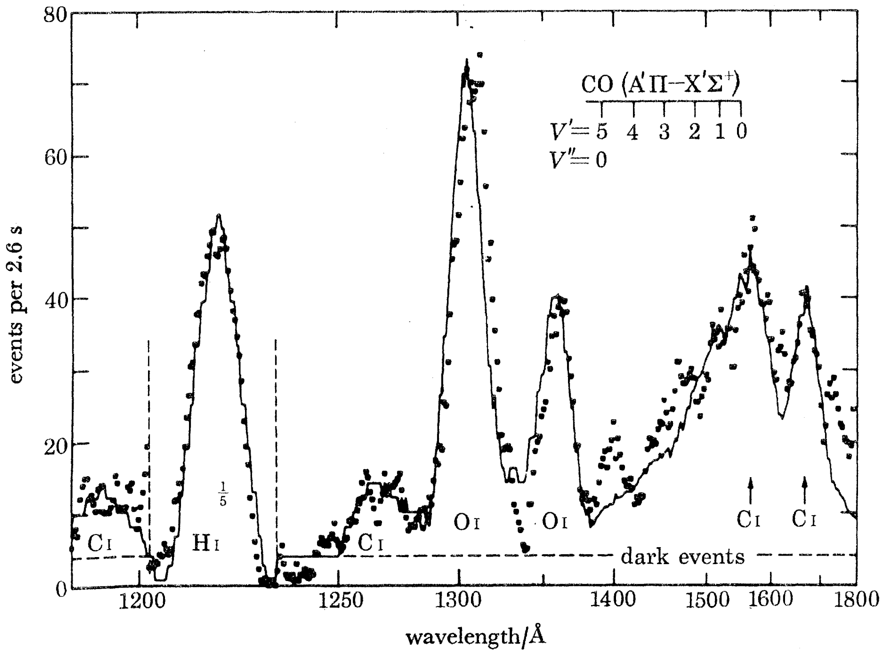

Figure 5. Spectrum of Venus obtained with rocket spectrometer.

The far u.v. spectrum of Jupiter (Rottman, Moos & Freer 1973), shown in figure 6, exhibits a Ly α emission which is twice as large as observed on a later rocket flight and 4 times as large as reported by a photometer on Pioneer 10 (Judge & Carlson 1974). This spectrum also indicates possible H_2 emissions. The signal above 1600 Å shows a large albedo which confirms the belief that there is a low concentration of molecular impurities in the Jupiter H_2 dominated upper part of the lower atmosphere.

These planetary studies have been very useful for planning and confirming spacecraft studies and for extending our spectroscopic knowledge beyond the capabilities of the spacecraft instrumentation.

5. Far u.v. background

The Apollo 17 UVS was also employed to search for a diffuse background source of far u.v. radiation during transearth coast. This was accomplished by long term observations of regions near the north and south galactic poles. These measurements were degraded at all wavelengths by the presence of a grating scattered light signal produced by solar system Ly α resonance radiation at 1216 Å. Previous measurements made from within the Earth's atmosphere (Henry 1973; Davidsen, Bowyer & Lampton 1974) have indicated an upper limit to the background flux of about 1000 photons $cm^{-2}\ s^{-1}\ Å^{-1}\ sr^{-1}$ but this entire signal may originate in the Earth's night glow or high altitude dust layer.

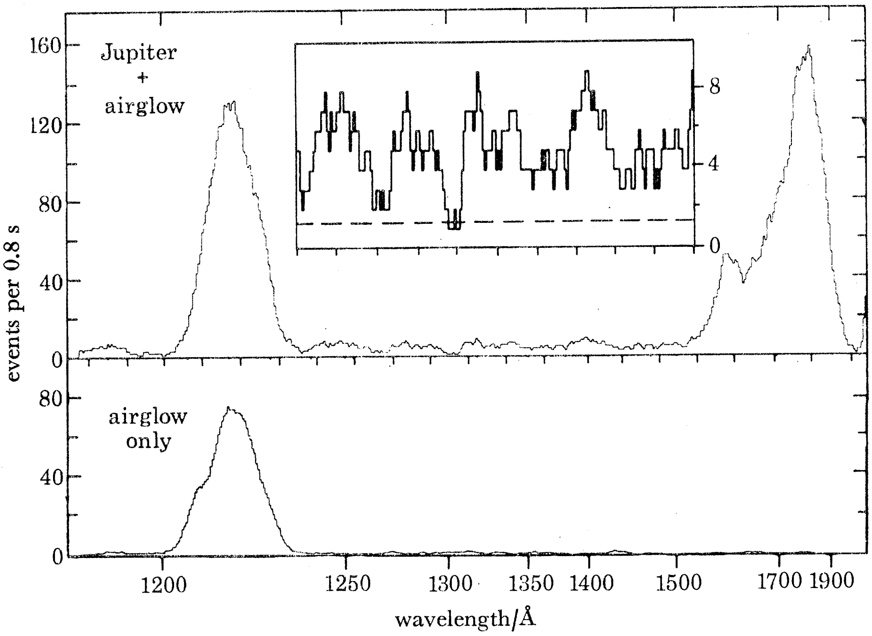

Figure 6. Rocket spectrum of Jupiter compared to airglow spectrum obtained with rocket spectrometer.

The solar Ly α signal scattered by the grating was accurately determined by comparison with the near Earth signal observed during the latter part of the return flight so that the residual u.v. background could be determined. At all wavelengths between 1300 and 1680 Å, the background signal was about 250 photons $cm^{-2}\ s^{-1}\ Å^{-1}\ sr^{-1}$ with an uncertainty of 1 σ of $\pm$ 150 photons $cm^{-2}\ s^{-1}\ Å^{-1}\ sr^{-1}$. Thus the total of solar system scattering, galactic scattering and other u.v. background sources is much smaller than indicated by previous measurements.

6. Lunar hydrogen

The Apollo 17 lunar atmosphere observations were negative (Fastie *et al.* 1973). No emission feature attributable to an atmospheric constituent was observed in the spectral range 1180–1680 Å. The upper limit of 10 atoms/cm^3 for atomic hydrogen is almost 3 orders of magnitude below the equilibrium density expected if solar wind protons are neutralized at the surface and escape as hydrogen atoms. If hydrogen molecules are produced the expected density of 3.6×10^3 molecules cm^{-3} is just below the detection limit for H_2 fluorescence (Feldman &

Fastie 1973). The assumption of conversion to H_2 by lunar dust grains seems a reasonable conclusion, and supports the hypothesis that H recombines on interstellar dust grains and perhaps suggests the accretion of H_2 on distant comets.

7. Comet Kohoutek (1973f)

Comet Kohoutek, also known as the Comet that Couldn't, was a disaster for public viewing, but the coordinated research that was performed will be most significant.

We observed emissions from the coma in the spectral range 1200–3150 Å on U.T. 5.1 January 1974 when the comet was 0.34 AU† from the Sun (Feldman, Takacs, Fastie & Donn 1974). The experiment was performed in an Aerobee 200 rocket launched from White Sands Missile Range, New Mexico, U.S.A. In addition to the emission features at 1216 Å (H I) and 3090 Å (OH) which were observed by OAO II from Comet Bennett (1970 II) we observed OI (1304 Å) and C (1560 and 1657 Å) (Feldman *et al.* 1974). The spectra are shown in figures 7 and 8. Emissions from CO, H_2 and CO_2 were not detected, but the brightness of the observed features lead us to conclude that H_2O and CO or CO_2 are the parent molecules of the atoms we detected in the coma spectrum.

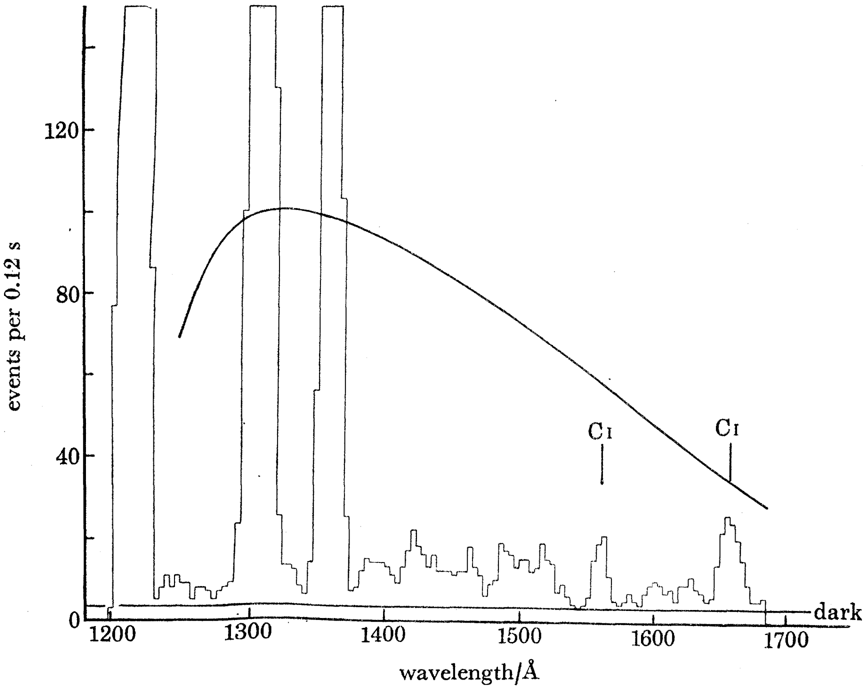

Figure 7. Far u.v. rocket spectrum of Comet Kohoutek.

On the basis of the brightness of the observed carbon lines we have concluded that the production or evaporation rate of CO_2 or CO is commensurate with the amount of water vapour produced in the coma.

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† 1 AU ≈ 1.5×10^{11} m.

In planning the experiment we hypothesized that a comet may evaporate a large amount of H_2 on its first near approach to the Sun. Although H_2 emissions were not observed, the progressive decrease in predicted brightness as Kohoutek approached the Sun suggests that its observed brightness at discovery may have been due to a dust coma produced by a highly volatile outer layer. H_2 formed from atomic hydrogen accumulated by the comet during its travels through interstellar space could possibly provide the proposed outer layer.

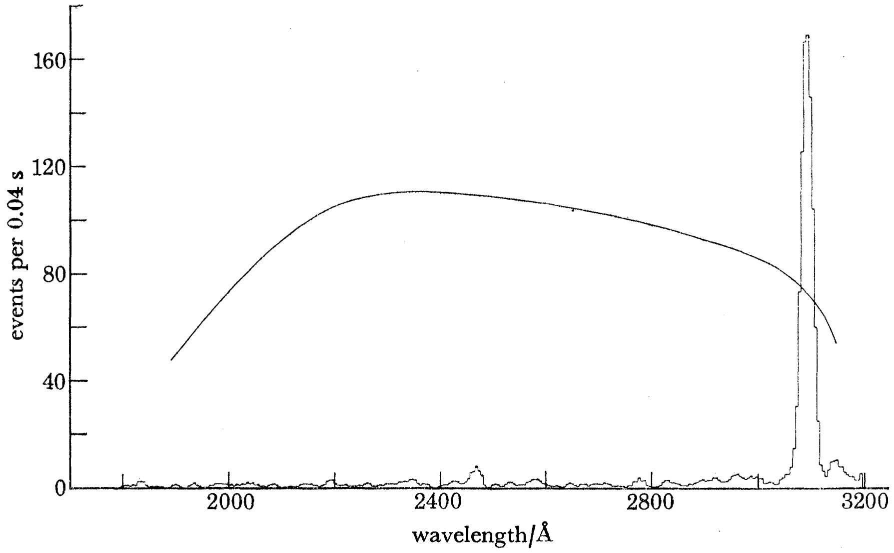

Figure 8. Rocket spectrum of Comet Kohoutek in the region 1800–3200 Å. To date the only emissions which have been positively identified as of cometary origin are OH at 3060 and 3142 Å.

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