FLUORESCENCE EQUILIBRIUM IN THE ULTRAVIOLET SPECTRA OF COMETS SEARGENT (1978m) AND BRADFIELD (1979ℓ)

Michael F. A'Hearn and David G. Schleicher
University of Maryland

Bertram Donn, Goddard Space Flight Center

William M. Jackson, Howard University

ABSTRACT

We have carried out detailed fluorescence calculations for OH including the Swings effect. These calculations have been used to reproduce the high resolution spectra of Comets Seargent and Bradfield taken with IUE. There does not seem to be any evidence of a need for an additional population of thermalized OH radicals as suggested by some other investigators. The calculations also provide the OH fluorescence efficiencies (g factors), as a function of heliocentric radial velocity, which are needed to derive OH abundances from measured fluxes. A close examination of the spectra shows no sign of the corresponding emission bands of OD allowing us to place upper limits on the ratio N(OD)/N(OH). Preliminary attempts to reproduce the CO^+ band structure by fluorescence will also be discussed.

INTRODUCTION

As remarked by the previous speakers, derivation of abundances and production rates in comets usually assumes that the species being studied is in fluorescent equilibrium. With the exception of a few cases, this assumption has been studied and found to be true for most species observed in the optical. The assumption is much less well tested in the ultraviolet. In order to validate the assumption of fluorescent equilibrium, one must be able to reproduce all aspects of the observed spectrum. In this talk, we will consider two species, both of which have been studied to some extent previously, OH and CO^+. The observational data consist of several post-perihelion spectra of Comet Seargent (1978m) taken at $r_H \sim .9$ AU and $\dot{r}_H = +34$ km/sec plus very many spectra of Comet Bradfield (1979ℓ) taken at 0.7 AU $\leq r_H \leq 1.5$ AU and 24 km/s < $\dot{r}_H$ < 28 km/s. The spectra of Comet Seargent have been described briefly by Jackson et al.[1] and those of Comet Bradfield by Feldman et al.[2]

<u>OH</u> The OH radical has been studied at both high and low resolution. Three bands have been observed: the 0-0 band at λλ 3080-90, the 1-1 band at λλ 3130-3150, and the 1-0 band at λλ 2800-2850. From ground-based observations of the 0-0 band, it has long been known that these bands exhibit a large Swings effect. This alone proves that fluorescence plays an important role in the equilibrium of OH but not necessarily that fluorescence is the only important mechanism.

We have carried out an extensive calculation of the fluorescence equilibrium of OH, including the Swings effect. For the calculations we have included 3 vibrational levels and 5 rotational levels in each electronic state, as well as the Λ-doubling of the levels. For the solar flux we have used the atlas of Kohl, Parkinson, and Kurucz[3] while the oscillator strengths for the various transitions have been taken from a variety of sources. The calculations predict both the integrated intensities of the bands and their detailed structure as a function of heliocentric distance and heliocentric radial velocity. (Details of the calculations will be presented elsewhere.)

The relative intensities of the 1-0, 1-1, and 0-0 bands are predicted to be 1:1:8:50 at the radial velocities of the Bradfield observations. This is in good agreement (10%) with the observed low-dispersion spectra. The 0-0 and 1-0 bands have also been examined at high resolution. Figure 1 shows the 0-0 band of Comet Bradfield at $r_H = 0.71$ AU and $\dot{r}_H = 24.0$ km/sec. The dashed vertical lines represent the strengths of the lines as calculated for pure fluorescence equilibrium and then multiplied by the wavelength dependence of the long wave low dispersion camera. Because this band is near the edge of the camera response, there is almost 40% variation in sensitivity across the band. Clearly the agreement between theory and observation is excellent in this case. The fact that the longest wavelength theoretical lines are too strong by 10 to 15% may be due to either the use of the low dispersion sensitivity curve in the high-dispersion mode or to errors in the ripple-correction of the observed spectrum. This particular discrepancy does not appear to be due to a defect in the theory. Four lines are marked A through D since the ratios A/B and C/D exhibit the Swings effect most strikingly.

To investigate optical depth effects, we have used the column densities of OH derived from the low dispersion spectra combined with the theoretical calculation which predicts that, for this radial velocity, nearly all of the OH radicals are approximately evenly split between the 2 Λ-doubled components of the ground state ($^2\Pi_{3/2}$, $J = 3/2$, $K = 1$). The effective cross-section at the line center also depends on the velocity dispersion of the OH radicals. If we assume a velocity dispersion of 1 km/sec, we derive an optical depth at the line center of order unity for either of the strong lines arising from the ground state. These lines are the ones labelled A and B in Figure 1. The optical depth in any other lines should be significantly lower. Because the theoretical predictions (which assume negligible optical depth) agree so well with the observations we conclude that the velocity dispersion is sufficiently higher than the 1 km/sec assumed above that the line center optical depth is much less than unity.

The dramatic Swings effect is shown by comparing Figure 1 with Figure 2, which is the spectrum of Comet Seargent obtained at $r_H = 0.93$ AU and $\dot{r}_H = +34.0$ km/sec. According to theory, the change in heliocentric distance should have only very small effects on the spectrum so that the large differences are due to the change in radial velocity from +24 to +34 km/s. Note particularly the ratios A/B and C/D in the two figures. The theoretical calculations for Comet Seargent do not agree with observation as well as in the case of Comet Bradfield although we still have agreement within about 25% on all lines. Differences between the two cases include: 1. somewhat different IUE data processing, 2. Comet Seargent was somewhat brighter and at greater heliocentric distance so that optical depth effects may be noticeable, 3. the difference in the relative populations of the 2 Λ-doubled levels of the ground state may allow collisional effects to appear. At present, however, we feel that the agreement is good enough that further processes, although possibly significant, can not be justified on the basis of this data alone.

To further test the fluorescence predictions we have examined the 1-0 band in Comet Bradfield as shown in Figure 3 which is taken from the same spectrum as Figure 1. Because the 1-0 band has only .02 the intensity of the 0-0 band, the signal-to-noise ratio in Figure 2 is considerably worse than in Figure 1. Nevertheless, the agreement between theory and observation is excellent. Furthermore, we have extracted one emission line from 2 adjacent orders, as shown in the figure, and it tends to confirm our hypothesis that the echelle ripple correction is the cause of the discrepancy at the long-wavelength end of Figure 1. Note that in Figure 3, there has been no correction for the spectral sensitivity of the IUE spectrograph system because the low-disperion system varies in sensitivity by only 2% across Figure 3.

Another aspect of the OH spectrum is the study of the isotopically shifted bands expected from O^2H. A careful examination of the spectrum of Comet Seargent shows no trace of the O^2H bands and, assuming that both forms are in fluorescent equilibrium, this allows us to set an upper limit on the column density ratio $N(O^2H)/N(O^1H) \leq .01$. Much longer exposures on Comet Bradfield, not yet analyzed, will provide us greatly improved sensitivity for this determination.

Summarizing our work on OH, we feel that pure fluorescence equilibrium adequately describes the data thus far obtained. We now move to another species for which we will derive exactly the opposite conclusion.

<u>CO^+</u> The First Negative system of CO^+ ($B^2\,\Sigma^+ - X^2\,\Sigma^+$) was identified in rocket spectra of Comet West by Feldman and Brune[3] and by Smith et al. (private communication). The spectra showed the $\Delta V = +1, 0, -1,$ and -2 sequences. The IUE spectra of both Comets Seargent and Bradfield, however, show a completely different structure for the CO^+ bands. Because these bands are weak compared to those of OH, we have studied them only in low resolution spectra. Figure 4 shows the relevant portion of a low resolution spectrum of Comet Bradfield. The origins of many of the CO^+ bands are also shown.

Krishna-Swamy[4] has carried out a fluorescence calcuation for CO^+ to predict the relative intensities of the different bands and according to his predictions the $\Delta V = 0$ sequence should be the strongest sequence. This is what was observed in Comet West but appears not to be true for Comets Seargent and Bradfield, in both of which the $\Delta V = 0$ sequence is entirely absent. Because Krishna-Swamy gave only relative band strengths with no calibration to absolute number of molecules and because he used a solar atlas which, at these wavelengths, seems to have serious systematic errors, we have begun our own calculations of CO^+ fluorescence in an attempt to explain our anomalous data. For a preliminary calculation we have omitted the Swings effect (as did Krishna-Swamy) because the rapid acceleration of CO^+ ions should smear out the heliocentric radial velocities enough that the Swings effect is negligible. Also for our preliminary calculations, which serve mainly to provide an absolute scale for the fluorescence efficiency, we have omitted B-A (Baldet Johnson) and A-X (Comet Tail) Systems. We derive somewhat different intensity ratios than did Krishna-Swamy, but we still find that the $\Delta V = 0$ sequence should be as strong as the $\Delta V = -1$ sequence.

In order to investigate the possibility of optical depth effects, suggested as a possibility in our paper describing the original Bradfield results (Feldman et al. 1980), we have assumed that the feature at λ 2310 is indeed the $\Delta V = -1$ sequence of CO^+ and that it is fluorescently pumped. This yields a column density of CO^+ only 1% of that of OH in Comet Bradfield. This in turn implies that the optical depth in the $\Delta V = 0$ sequence of CO^+ is less than that of OH, probably a few tenths. If the velocity dispersion of CO^+ is significantly greater than 1 km/sec, as one would expect, then the optical depth is negligible. Optical depths, therefore, can not explain the anomalous intensities.

One other significant difference between these observations and those of Comet West is that IUE observes only a small region near the nucleus while the rocket spectra of Comet West sampled most of the coma. If these spectral features are indeed CO^+, then possibly we are seeing highly vibrationally excited bands (e.g., 4-4 and 5-5) which might be due either to collisions or to direct production of CO^+ in excited states. Even these hypotheses are difficult to accept because they must completely overwhelm the fluorescence mechanism. In any case, it is clear that these emission features are not due to CO^+ in fluorescent equilibrium.

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Further analysis by A'Hearn and Feldman suggests that the "CO^+" bands are, in fact, not due to CO^+. The feature at λ 2310 is due to the Mulliken bands of singlet C_2, while the feature at λ 2430 is due to Lyman alpha in second order.

REFERENCES

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4. Feldman, P. D. and W. H. Brune: 1976 Ap.J. 209, L45.

5. Krishna-Swamy, K.S.: 1979 Ap. J. 227, 1082.

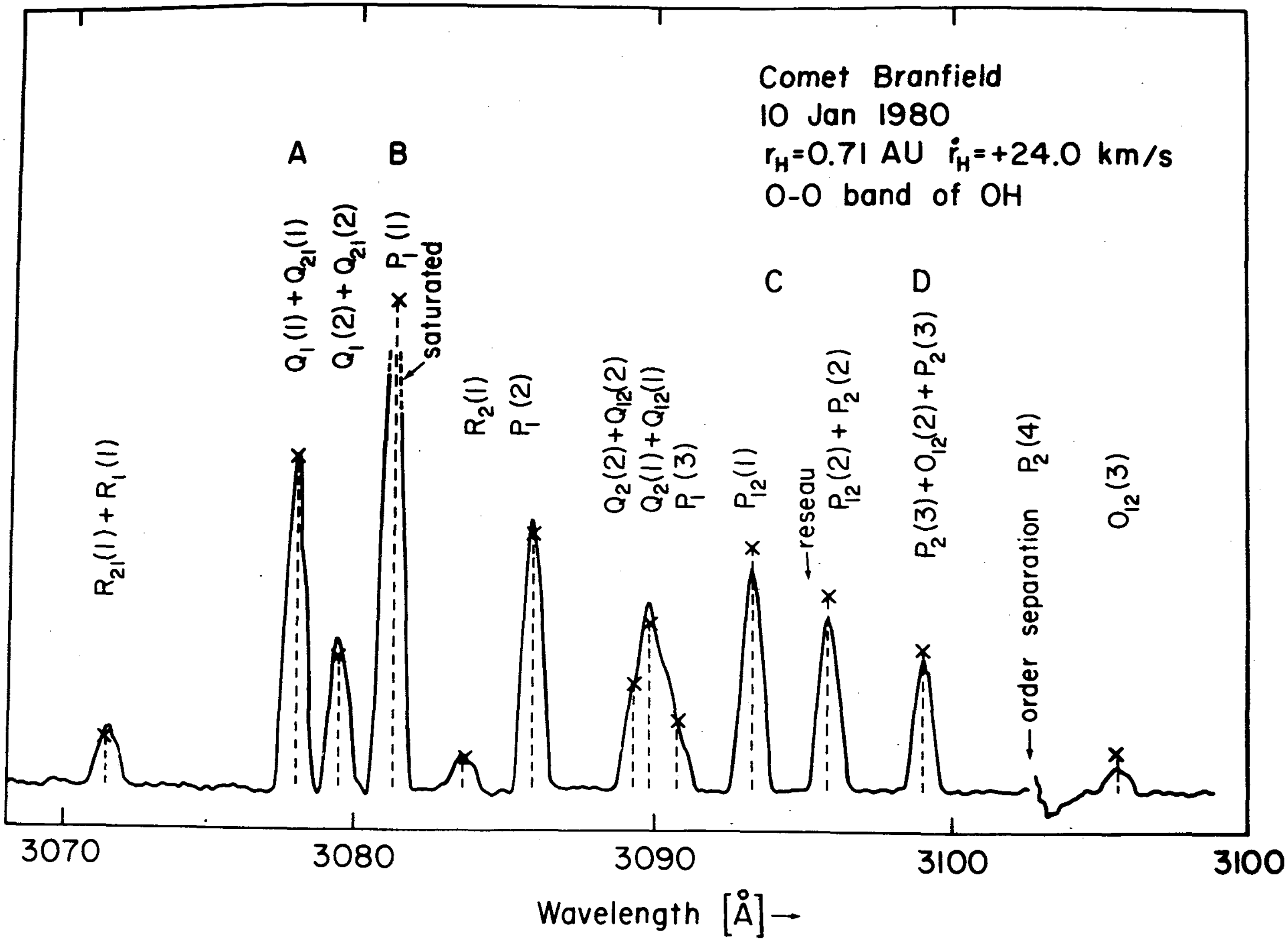

Fig. 1: High-dispersion spectrum of 0-0 band of OH in Comet Bradfield. Dashed vertical lines are the theoretical line intensities based on pure fluorescence equilibrium. Compare the line ratios A/B and C/D in this figure and Figure 2.

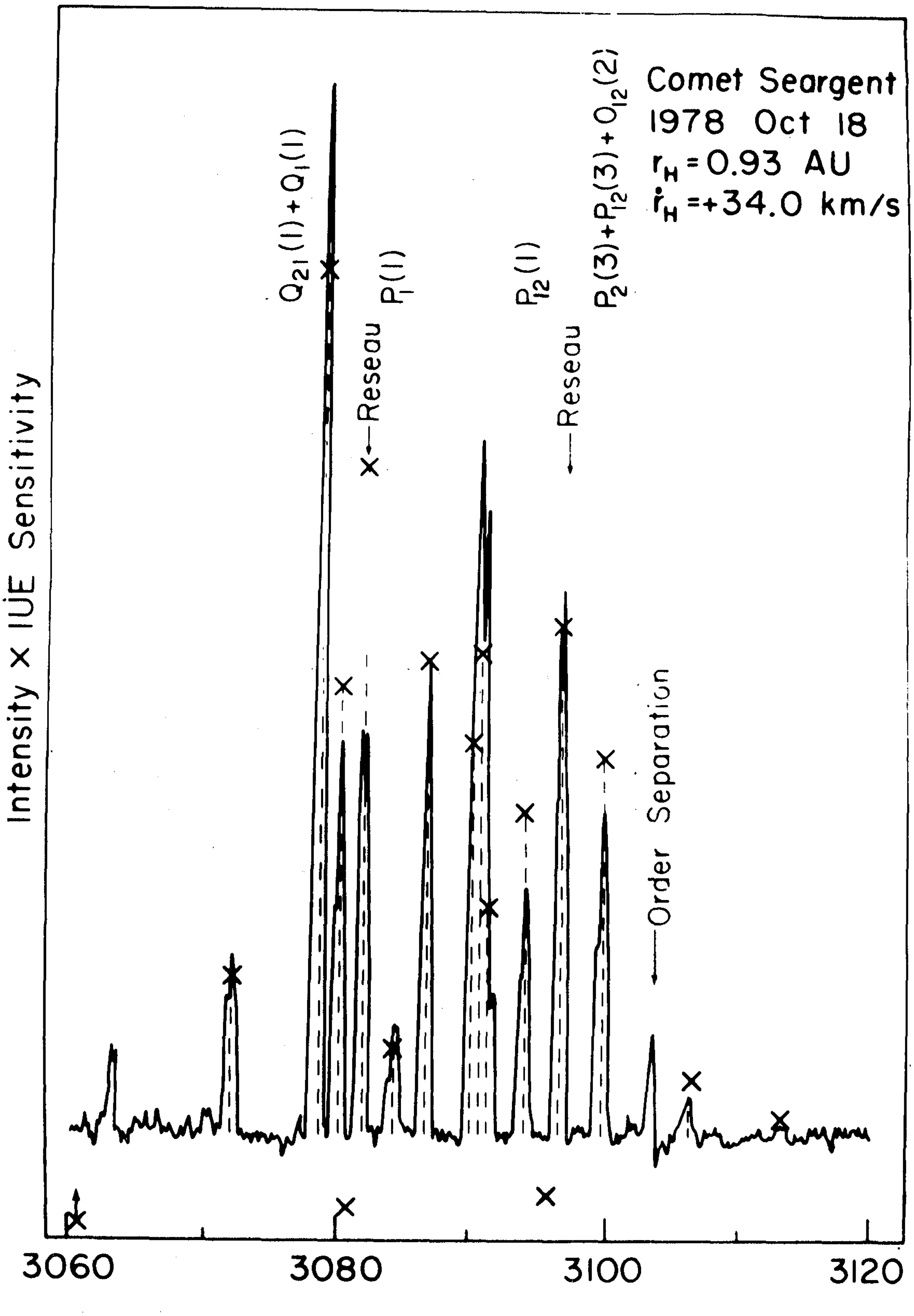

Fig. 2: High-dispersion spectrum of 0-0 band of OH in Comet Seargent.

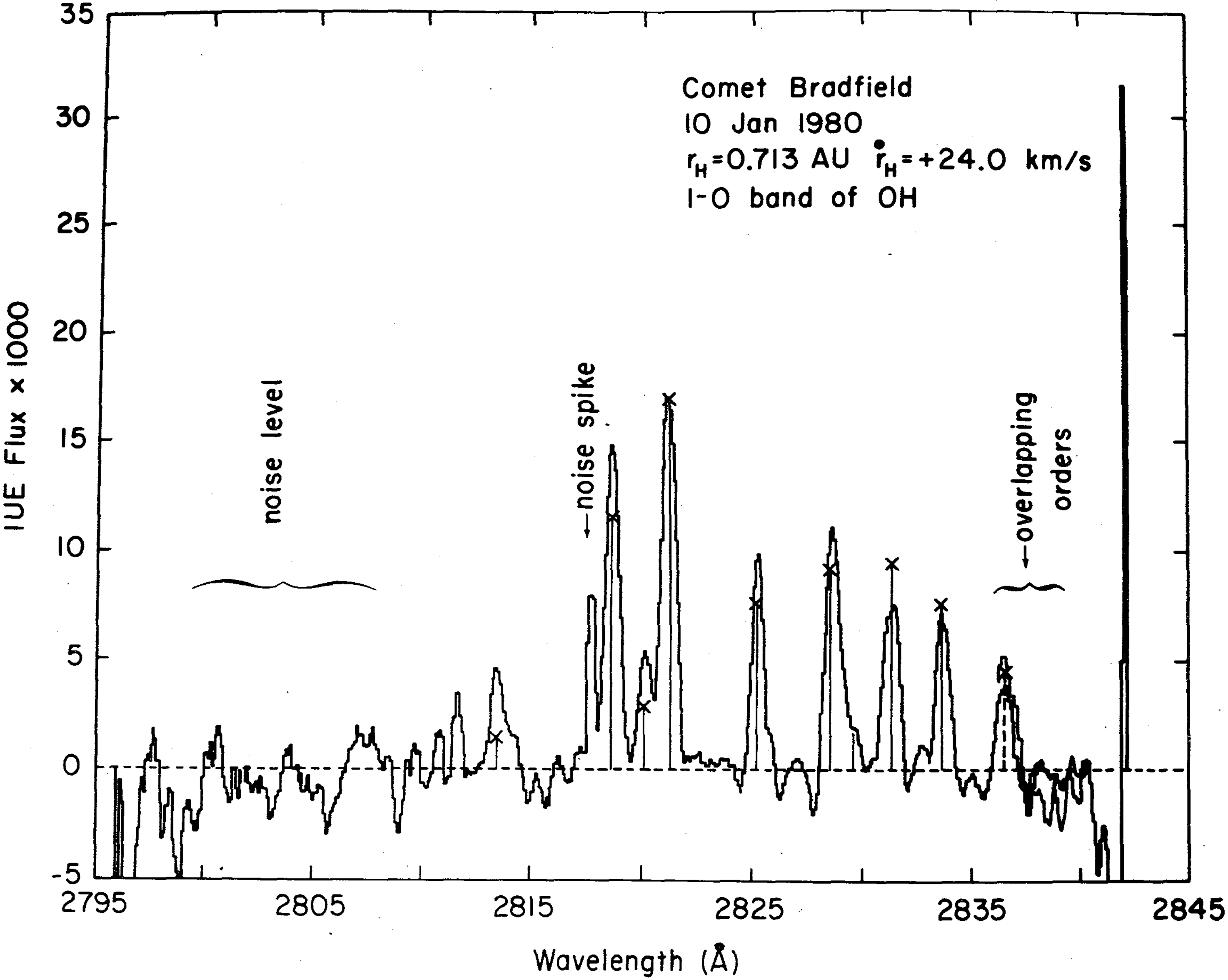

Fig. 3: High-dispersion spectrum of 1-0 band of OH in Comet Bradfield. Taken from same exposure as Figure 1.

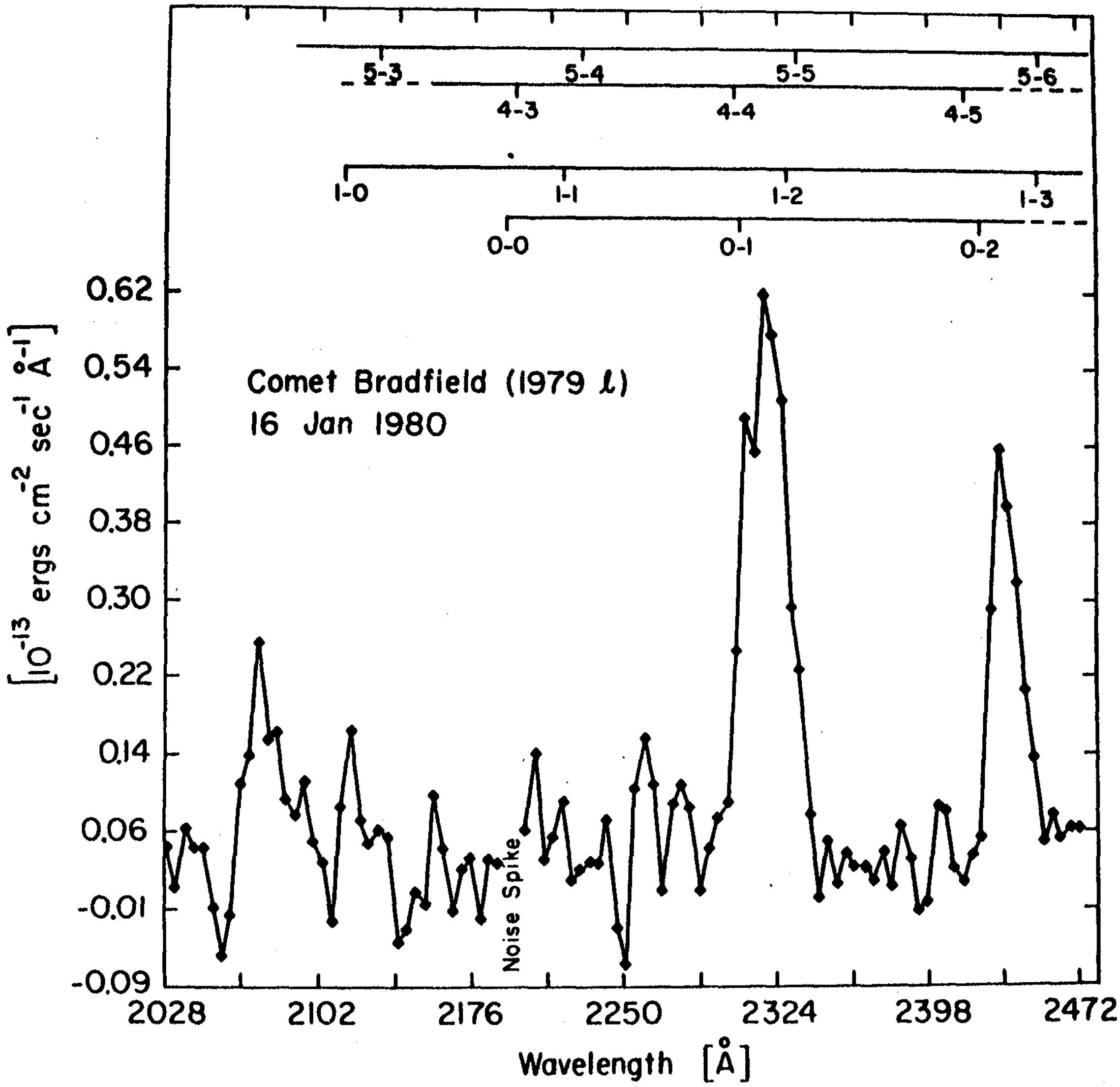

Fig. 4: Low-dispersion spectrum of Comet Bradfield in the region of the CO^+ bands. Origins of various CO^+ bands are indicated.