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SPECTROGRAPHIC OBSERVATIONS OF COMET WEST (1975 *n*)

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The spectrum of comet West (1975 *n*) was recorded on 1976 March 7 and 11 in the wavelength interval 5700 Å–8200 Å at an intermediate resolution. One hundred and twenty-two emission lines are reported with 78 lines having identifications with spectral features of NH_2, H_2O^+, C_2, [O I], and Na I.

Key words: spectroscopy — comet

I. Introduction

The apparition of comet West (1975 *n*) provided an opportunity for a program of spectrographic observations of an unusually bright comet. The comet was significant in terms of its brightness and activity. It reached a total visual magnitude of −3 during perihelion passage (Marsden 1976*c*). The multiple splitting of the nucleus into four parts, the production of the "synchronic" bands in the dust tail, and the strong continuum of the observed spectra were indicative of the activity of the comet (Sekanina 1976). Comet West is new in the Oort-Schmidt (1951) classification, although not at the extreme early-age end. The semi-major axis is between 500–5000 AU (Marsden 1976*b*,*d*). It would not have come, on this apparition, directly from the Oort cloud of some 50,000 to 150,000 AU in distance (Oort 1950). Hence, it is different from the "new" comets, e.g., Kohoutek (1973 XII), but displayed the friability expected of "new" comets.

Comet West's photometric variation was greater than the predicted r^{-4} heliocentric dependence and was nearer $r^{-5.5}$ as reflected in the *IAU Circulars*. The subsequent brightness of comet West allowed observations between 5700 Å and 8200 Å at 5 Å mm^{-1} dispersion with an *F*/5 spectrograph. On 1976 March 7 and March 11 two spectrograms of comet West were obtained with the echelle diffuse-light spectrograph at the George C. Marshall Space Flight Center, Huntsville, Alabama. On these dates the comet (total visual magnitude ~2) had a heliocentric distance, *r*, and a geocentric distance, Δ, (Marsden 1976*a*) in astronomical units given by

March 7 $r = 0.45$ $\Delta = 0.88$

March 11 $r = 0.53$ $\Delta = 0.92$.

The analysis of the spectrographic plates is reported below with 122 lines observed and 78 lines identified.

II. The Observations

The spectrograph employed for the observations has been described by Gull, O'Dell, and Parker (1974). It uses an echelle grating primary-disperser with a low-order grating used as a cross-disperser. The system's objective and collimator lenses were changed from the original configuration for these observations. The objective and collimator lenses employed were identical 12.7-cm diameter (fl = 60 cm) achromatic refractor lenses.

The observations were made with an S-20 cathode, ITT F4708 electrostatic focus, fiber-optics-coupled image tube of 40 mm diameter. The system's spectral resolution with the image-tube distortions averaged about 0.5 Å on the photographic plates, which are in direct contact with the image-tube fiber optics output plate.

The linear reciprocal dispersion (*K*, in Å mm^{-1}) varies with wavelength (λ, in Å) as $K \simeq 10^{-3} \times \lambda$. The measured value at 5850 Å is 5.26 Å mm^{-1}. A linear element of 25 μm projects to 75 μm at the entrance slit; this corresponds to an angular size of 0.37 arc minutes. The slit (75 μ × 2 mm) was centered on the comet's coma and was oriented along the direction of the tail. The cross disperser was set to observe in the 1st order, with filtering employed to block higher-order overlaps. The echelle grating was set to cover the 30th through 42nd orders. The useful spectral range for these measurements extended from about 5700 Å to 8200 Å, and was recorded on 5 cm × 5 cm Kodak IIa-D photographic plates which were baked to increase sensitivity.

The March 7 plate was subjected to successful post-development processing (Askins 1976*a*,*b*), which allowed intensification and increase in the contrast of the spectrum. This technique involves the radio-activation of the plate by chemical attachment of molecules containing unstable S^{35} to the developed silver atoms in the emulsion, regardless of position with respect to developed grains. The resulting plate is contacted to an X-ray emulsion upon which the decaying atoms record their presence by beta-particle tracks, which are then developed.

III. Measurements

The spectral range recorded on the photographic plates was determined by the tilt of the gratings and the size of the image tube in the focal plane of the camera and the resultant spectral data was not contiguous through the spectral range covered. Table I gives the approximate minimum and maximum wavelength per echelle order for both observations.

An empirical procedure for determination of the cometary wavelength provided an efficient method which accounted for nonlinear distortion of the image tube and allowed identification of low-contrast features. Each echelle order, photographically enlarged to about 12 times the scale of the original cometary spectrum, together with its neon comparison lines, was cross-calibrated graphically with a solar spectrum of the same order, grating settings, and comparison lines. Wavelength identifications of solar spectral features were plotted as a function of position on the enlarged spectrum. The corresponding cometary spectrum was vertically displaced from the solar spectrum in order that the position-wavelength function that was generated could be used to determine the wavelength of cometary features.

The resulting wavelength calibrations have uncertainties of approximately ± 0.75 Å; however, for identification purposes, the value of ± 1.5 Å was assumed because of the difficulty in certain regions to determine an interpolation or extrapolation value. The wavelength determinations of the original plates of March 11 and the intensification plate of March 7 were carried out for all features appearing on the continuum of the cometary spectra. Table II contains the wavelengths measured from the March 7 intensified plate and the March 11 original plate adjusted for Doppler shift due to the geocentric radial velocity of the comet, along with possible atomic and molecular identifications. Due to the low contrast resulting from the strength of the reflection continuum of comet West, the reality of many weak features initially measured were in doubt. We selected from this original group only those lines that were quite strong or that had wavelength correlations between the two plates, and those having good correlations with features of the NH_2 laboratory spectrum. Therefore, the credence of the reported spectral lines in Table II is probably quite good. The identifications are based on Richter (1963), Dressler and Ramsay (1959), Chamberlain (1961), Moore (1959), Greenstein and Arpigny (1962), Woszczyk (1962), Pearse and Gaydon (1963), Davis and Phillips (1963), Phillips and Davis (1968), Wehinger et al. (1974), Dossin et al. (1961), Fehrenbach and Arpigny (1973), Wyckoff and Wehinger (1976), Arpigny (1965), O'Dell (1971), Phillips (1948), Ballik and Ramsay (1963), Kohoutek and Rahe (1976), Herzberg (1939, 1966), Herzberg and Ramsay (1955).

Unfortunately, the variation in response across each spectrum prevented the determination of intensity data for the emission lines that were identified. Each echelle order has a wide variation in blaze efficiency across a few hundred angstroms wavelength interval.

TABLE I

SPECTRAL REGIONS MEASURED

March 7 Plate		March 11 Plate	
Order	Range (Å)	Order	Range (Å)
41	5810-5915	42	5660-5800
40	5945-6070	41	5780-5925
39	6095-6230	40	5920-6090
38	6255-6410	39	6070-6250
37	6440-6615	38	6245-6430
36	6600-6810	37	6425-6610
35	6800-7020	36	6590-6790
34	7010-7220	35	6808-6990
33	7235-7460	34	7024-7245
32	7470-7680	33	7240-7440
31	7735-7930	32	7480-7680
30	8000-8220	31	7745-7950
		30	8000-8130

TABLE II

COMETARY EMISSION FEATURES

λ Observed (Å)	Identifications*
5712.5	---
5720.6	NH_2 (0.6)(0,10,0) 3_{12}-3_{22}, 2_{12}-2_{20}
5731.4	NH_2 (1.7)(0,10,0) 1_{10}-2_{20}, 1_{11}-2_{21}
5740.8	NH_2 (1.3)(0,10,0) 2_{12}-3_{22}, 2_{11}-3_{21}
5815.1	---
5827.9	H_2O^+ (6.7)(9-0) 2_{21}-1_{11}
5882.6	---
5889.9	NaI D_2 (0.0)
5896.3	NaI D_1 (5.9)
5925.1	NH_2 (6.3) Em
5947.6	---
5956.5	NH_2 (5.6) Em
5959.0	NH_2 (8.9)(0,9,0) 7_{07}-6_{15}; C_2 (8.7)(4,6) head
5976.5	NH_2 (6.5)(0,9,0) 5_{05}-5_{15}, 1_{10}-1_{11}; (6.8) Em

TABLE II (Continued)

λ Observed (Å)	Identifications*
5978.4	NH_2 (7.2)(0,9,0) 3_{03}-3_{13}, 4_{04}-4_{14}; (7.3) 3_{03}-3_{12}, 4_{04}-4_{14}
5986.3	NH_2 (6.5)(7.4)(0,9,0) 6_{25}-5_{15}
5990.5	---
5995.6	NH_2 (5.0)(0,9,0) 1_{01}-2_{11}
6002.9	---
6007.6	NH_2 (7.0)(0,9,0) 2_{02}-3_{12}
6044.6	NH_2 (5.8)(0,9,0) 5_{05}-6_{15}
6045.9	NH_2 (6.5)(0,9,0) 5_{05}-6_{15}
6121.8	C_2 (2.2)(1,3) head; NH_2 (1.1) (0,9,0) 4_{23}-5_{33}
6133.5	NH_2 (3.4)(4.0)(0,9,0) 5_{24}-6_{34}
6135.2	H_2O^+ (4.7)(8-0) 3_{12}-2_{02}
6140.0	H_2O^+ (0.5)(8-0) 2_{11}-0_{01}
6141.1	H_2O^+ (0.9)(8-0) 2_{11}-0_{01}
6150.8	---
6156.6	OI (7.0) (Sky?)
6158.5	H_2O^+ (8.6)(8.7)(8-0) 2_{12}-2_{02}
6175.2	---
6177.2	---
6198.7	NH_2 (9.5) Em?; H_2O^+ (8.8)(8-0) 1_{10}-2_{20}
6261.8	NH_2 (2.1) Em
6263.5	NH_2 (3.2) Em
6271.5	---
6275.0	NH_2 (4.3)(6.0)(0,8,0) 3_{12}-2_{02}
6284.3	NH_2 (5.0)(0,8,0) 1_{10}-0_{00}
6286.0	NH_2 (6.2)(0,8,0) 1_{10}-0_{00}
6290.3	---
6292.7	NH_2 (2.4)(2.9)(0,8,0) 5_{14}-4_{22}
6293.9	CN (3.7)(10,5) R_1
6297.9	NH_2 (7.6)(0,8,0) 3_{12}-3_{20}
6299.7	NH_2 (8.7)(0,8,0) 2_{12}-2_{02}; (9.5)(0,8,0) 6_{16}-6_{06}
6301.4	[OI] (0.4); NH_2 (0.1)(0,8,0) 6_{16}-6_{06}
6317.5	NH_2 (7.9)(8.6)(0,8,0) 2_{11}-2_{21}
6321.3	NH_2 (0.4)(0,8,0) 2_{12}-2_{20}; (0.6)(0.8) (0,8,0) 3_{12}-3_{22}
6322.3	NH_2 (2.4)(0,8,0) 3_{12}-3_{22}
6324.6	NH_2 (4.1)(0,8,0) 4_{13}-4_{23}; NH_2 (5.1) Em
6327.3	NH_2 (7.0)(7.2)(7.7)(0,8,0) 5_{14}-5_{24}
6330.2	NH_2 (1.4)(0,8,0) 7_{16}-7_{26}

TABLE II (Continued)

λ Observed (Å)	Identifications*
6336.4	---
6346.9	NH_2 (5.4)(6.4)(0,8,0) 2_{11}-3_{21}
6348.5	---
6351.6	---
6353.5	NH_2 (4.6) Em; CO^+ (4.) R_1?
6355.3	NH_2 (5.5)(0,9,0) 3_{12}-4_{23}; NH_2 (5.0) Em; CN (5.1) Q_1
6362.5	[OI] (3.9)
6364.0	NH_2 (3.8) Em?
6461.3	---
6468.7	---
6473.9	---
6476.2	NH_2 (7.0) Em
6480.5	C_2 (0.5)(5,8) head; NH_2 (0.7) Em
6483.0	NH_2 (3.0) Em
6485.9	---
6486.8	---
6493.7	CN (4.1)(6,2) R_1
6494.6	NH_2 (4.3)(4.6) Em
6495.8	NH_2 (5.3) Em
6497.3	---
6497.7	---
6499.2	---
6501.5	NH_2 (1.7)(0,8,0) 5_{32}-5_{42}, 4_{32}-4_{40}
6502.6	CN (2.3)(6,2) Q_1
6517.8	---
6526.4	NH_2 (7.3) Em; H_2O^+ (5.2)(7-0) 3_{03}-2_{11}
6549.0	NH_2 (9.7) Em
6556.4	---
6563.3	H α (2.8); H_2O^+ (2.8)(7-0) 1_{10}-2_{11}
6577.7	H_2O^+ (6.8)(7.3)(7-0) 2_{02}-3_{12}; H_2O^+ (7.7) unassigned
6592.6	H_2O^+ (2.8)(7-0) 3_{03}-4_{13}
6593.9	NH_2 (4.3) Em; H_2O^+ (3.3)(7-0) 3_{21}-3_{13}; H_2O^+ (3.1)(7-0) 3_{03}-4_{13}; H_2O^+ (3.5) (7.0) 4_{22}-4_{14}
6607.7	NH_2 (8.2) Em?
6610.5	---
6614.5	NH_2 (4.2)(0,7,0) 7_{07}-7_{17}
6615.9	---
6641.1	NH_2 (0.8)(0,7,0) 1_{10}-2_{11}

TABLE II (Continued)

λ Observed (Å)	Identifications*
6643.2	---
6648.5	CN (8.1)(7,3) R_1
6650.3	---
6656.8	NH_2 (5.7)(0,7,0) 2_{02}-3_{12}; (6.0) (0,7,0) 3_{21}-2_{11}
6657.3	CN (6.6)(7,3) Q_1
6662.3	---
6662.8	---
6663.7	---
6667.0	---
6670.3	NH_2 (0.4) Em
6670.8	NH_2 (1.0)(0,7,0) 3_{21}-3_{13}
6673.3	NH_2 (3.0)(0,7,0) 6_{25}-5_{33}
6681.2	NH_2 (1.9)(0,7,0) 2_{21}-2_{11}
6720.9	---
6724.1	NH_2 (4.2) Em
6741.3	NH_2 (1.2) Em
6770.3	---
6783.8	---
6807.2	---
6821.8	---
6824.9	---
7023.0	NH_2 (3.7)(0,7,0) 2_{12}-3_{22}
7040.3	H_2O^+ (0.7)(6-0) 1_{10}-2_{20}
7041.3	NH_2 (1.7) Em?
7054.5	H_2O^+ (5.1)(6-0) 2_{12}-3_{22}
7056.9	NH_2 (6.9) Em
7269.5	NH_2 (9.6) Em?
7283.9	CN (3.)(5,2) Q_1
7491.9	---
7533.5	---
7544.4	---
7756.2	---
7759.4	---
8049.2	---

* The general notation follows the notation for NH_2 when applicable: The atomic or molecular species, last two digits of the laboratory wavelength, the vibration band, and the rotational transition.

The light output from the image tube varies radially due to the use of curved fiber-optics plates, and the focus varies radially due to the electrostatic tube design. Emission-line visibility depends on the contrast with the underlying continuum (which also varies), so defocus toward the edge causes threshold detection level changes. Since these many factors enter to produce a significant and complex relation between threshold level and wavelength, we have not given even crude intensity data. Poor photometry is worse than no photometry for anything but exploratory studies, and we wish to provide usable identifications and wavelength data without giving misleading intensity data.

IV. Spectrum

On the data plates, the continuum of the comet dominates the spectrum along with the sodium D_1 and D_2 emssion lines at λ5890 and λ5896 and the [O I] λ6300 line. The additional features are much weaker and include the NH_2, C_2, and H_2O^+ emission. We discuss below the identifications that have been made.

1. *NH_2*

The coincidences of the observed lines with the triatomic molecule NH_2 were analyzed using the absorption data of Dressler and Ramsay (1959) and the emission data of Woszczyk (1962). The notation adopted for the NH_2 lines in Table II is

$$NH_2(X.Y)\,(\nu_1', \nu_2', \nu_3')\,N'_{k_a'k_c'} - N''_{k_a''k_c''}$$

or

$$NH_2\,(X.Y)\,\mathrm{Em}\quad,$$

with the convention: X and Y are the last two digits of the laboratory wavelength associated with the measured lines; ν_1' is the vibrational quantum number associated with the ith normal mode in the upper state; N is the total angular momentum excluding electron spin (the two components of the spin doublet are not differentiated); k_a and k_c are pseudo-quantum numbers obtained for symmetric molecules (Herzberg 1939, 1966). The lower level of the transitions is always the (0, 0, 0) vibrational level of the strongly bent $\tilde{X}^2B_1$ ground state. The excited state is the linear $\tilde{A}^2A_1$. Unassigned laboratory emission features are designated by Em.

The laboratory spectrum of NH_2 is extremely rich and some assumptions were necessary in comparing the comet spectrum with those from the laboratory. The principal assumption was that the excitation temperatures of the comet and laboratory source are about the same, hence the relative intensities should be comparable. This assumption is generally valid as a first order of approximation guide to identifying lines. Identifications were made with the (0, 10, 0), (0, 9, 0),

(0, 8, 0), and (0, 7, 0) bands but none were made with the (0, 3, 0), 0, 5, 0), or (0, 6, 0) bands which O'Dell's (1971) study of comet Tago-Sato Kosaka (1969 IX) has shown are characteristically weaker.

Within the stronger bands, a number of intensity anomalies were noted as indicated by missing members. Table III gives a listing of missing members from the strongest bands observed. Only missing lines whose laboratory intensities are comparable to other observed lines are given. As Woszczyk (1962) has noted, the Swings effect can cause the absence of some emission lines due to a solar absorption feature appearing at the Doppler-shifted wavelength of the transition exciting the upper state. This interpretation can account for the absence of the (0, 9, 0) 2_{21}–3_{31} and the (0, 9, 0) 3_{21}–4_{31} which is affected by the coincidence of the Mn λ6016.6 solar line with the (0, 9, 0) 2_{21}–1_{11} and (0, 9, 0) 3_{21}–2_{11} NH_2 lines. However, this interpretation cannot be applied to the remaining missing lines. In particular, it certainly cannot apply to those cases where the upper state is noted to give rise to a separate line which is observed (fourth column, Table III). Due to the varying detection threshold of our spectra, we have compared our list of missing NH_2 lines with the identification list of comet 1957 V (Woszczyk 1962). Eight of the lines were listed as being weak or missing in comet 1957 V even though four of these gave lines from the same upper state in comet West. This means that in both cases we have a genuine discrepancy in applying the believed energy structure of NH_2 and the resonance fluorescence mechanism to the observations. Of course, a clear-cut delineation of the NH_2 line discrepancy awaits a higher photometric accuracy study of at least a comparable spectral resolution as that used in this work.

A question mark on Table II indicates that the identifications are with laboratory lines of low intensity which would not be expected in the comet if

TABLE III

MISSING COMETARY NH_2 LINES HAVING STRONG LABORATORY STRENGTHS

Transition	Wavelength (Å)	Upper State Present	Seen in Comet Mrkos (1957V)*
(0, 10, 0) 2_{12}-2_{02}	5702.0 5703.0	Yes	Yes
(0, 10, 0) 4_{14}-4_{04}	5706.9 5707.0		Yes
(0, 10, 0) 6_{16}-6_{06}	5708.3 5708.4		WM
(0, 10, 0) 3_{30}-2_{20}	5811.3 5811.7		WM
(0, 9, 0) 3_{03}-2_{11}	5962.6 5962.7		Yes
(0, 9, 0) 7_{07}-7_{17}	5972.2	Yes	WM
(0, 9, 0) 2_{21}-1_{11}	6018.6 6020.3		WM
(0, 9, 0) 2_{21}-3_{31}	6096.7 6098.2		Yes
(0, 9, 0) 3_{21}-4_{31}	6108.9 6110.0		WM
(0, 8, 0) 7_{16}-6_{06}	6240.3 6240.6	Yes	WM
(0, 8, 0) 3_{12}-2_{02}	6274.3 6276.0	Yes	Yes

TABLE III (Continued)

Transition	Wavelength (Å)	Upper State Present	Seen in Comet Mrkos (1957V)*
$(0,8,0)1_{10}$-2_{20}	6331.6	Yes	
$(0,8,0)2_{12}$-3_{22}	6344.1 6344.1	Yes	WM
$(0,7,0)1_{10}$-1_{11}	6618.1 6618.1		Yes
$(0,7,0)3_{03}$-3_{13}	6619.3 6619.3		Yes
$(0,7,0)3_{21}$-2_{11}	6652.9 6656.0	Yes	WM
$(0,7,0)2_{21}$-1_{11}	6654.6 6659.2	Yes	Yes

* Yes indicates present, WM means weak or missing Woszczyk (1962).

the intensity distribution was similar to the laboratory sources.

2. *C_2*

The three bandheads λ5958.7 (4, 6), λ6122.2 (1, 3), and λ6480.5 (5, 8) of C_2 have been identified, but there were too few correlations between C_2 and comet lines to carry out further analysis on the C_2 molecule.

3. *H_2O^+*

Spectral correlations of H_2O^+ lines with the observed lines in comet West have been analyzed using the data of Wehinger et al. (1974). Thirteen lines have been identified with the H_2O^+ molecule. The predicted intensity distribution in the π-band at 6200 Å and the Σ, Δ complex at 6600 Å show that correlations of the observed lines with the expected most intense lines are relatively strong with the strongest lines of λ6159, λ6199, and λ6563 being observed.

4. *Atomic Species*

Correlations of the cometary lines with atomic transitions were analyzed using the multiplet table of Moore (1959). The following elements were studied, H I, He I, O I, [O I], O II, [O II], C I, [C I], C II, N I, [N I], N II, [N II], Fe I, [Fe I], Fe II, [Fe II], Si I, [Si I], Mg I, Mg II, S I, [S I], S II, and [S II].

The Hα (H I) identification was made; however, a strong H_2O^+ line also correlates with this cometary feature. The strength of the [O I] lines at 6300 Å and 6364 Å allows for a certain identification of these lines. The Na I D_1 and D_2 lines, as well as the λ6300 [O I], show a marked extension in the antisolar tailward direction. All other identifications were associated with the coma.

The lowest order of multiplets of O II and C II, which occur in the spectral range observed, have correlations with measured lines. For O II the lines at λ6721.6 and λ6640.9 of the 4th multiplet have correlations, and for C II the strongest line of the 2nd multiplet at λ6578.0 has a correlation with a measured line. However, the low number of correlations and other possible identifications for λ6578 and λ6721 lead to only tentative correlations with the recombination lines; therefore, they have not been identified in Table II.

5. *Molecular Spectra*

The following molecular species were searched for correlations without positive identifications: CO, H_2, N_2, O_2, HCO, HNO, NO_2, and O_3. Various other molecules that might be expected on the basis of the high cometary abundance of their constituents were also subjected to a literature search. In the case of CH, CH^+, CN^+, N_2^+, NH, NO, OH, OH^+, O_2^+, CH_2, C_3, and H_2O^+, no strong lines would be expected in the observed spectral range.

In summary, we can say that comet West presented the characteristic spectrum of a young comet, showing a strong continuum and several molecular and atomic species, including H_2O^+. There may be an intensity anomaly in trying to explain the NH_2 line-emission spectrum as due to single resonance fluorescence. However, a more-detailed theoretical analysis and spectral survey at higher photometric activity are

needed to resolve this apparent anomaly.

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