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SPECTROPHOTOMETRY OF COMETS GIACOBINI-ZINNER AND HALLEY

by

STEPHEN C. TEGLER

A THESIS SUBMITTED
IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE

MASTER OF SCIENCE

APPROVED, THESIS COMMITTEE:

C. R. O'Dell, Professor of Space
Physics and Astronomy, Chairman.

R. J. Dufour, Professor of Space
Physics and Astronomy.

F. B. Dunning, Professor of Space
Physics and Astronomy and of Physics.

HOUSTON, TEXAS

MAY 1987

Abstract

SPECTROPHOTOMETRY OF COMETS GIACOBINI-ZINNER AND HALLEY

Stephen C. Tegler

Observations have been made of Comet Giacobini-Zinner over the wavelength interval 3000 Å - 5700 Å and of Comet Halley over the wavelength interval 3000 Å - 10,000 Å. A photoelectric spectrophotometer with a 40 Å bandpass in the second order was used. Band fluxes from OH and CN have been obtained for Giacobini-Zinner. Band fluxes from OH, NH, C₂, and CN have been obtained for Halley. Swan band sequence flux ratios have been calculated for Halley and compared to resonance fluorescence theory and previous observations. The comparison suggests a reexamination of the molecular constants used in theoretical calculations and the validity of the statistical equilibrium assumption.

Acknowledgments

I wish to thank my parents, Harry and Dorothy Tegler, who gave me the support and guidance throughout my life that enabled me to undertake this work. I would also like to thank Dr. C. R. O'Dell for introducing me to optical astronomy and cometary science and providing the guidance to complete this work. Thanks also go to Patralekha Mitra for "being there" during the pitfalls and triumphs of graduate school. I would like to thank Maria Rondon for typing the thesis.

This work was supported by NASA grant NAG 8-485 and NSF grant AST-8505031.

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I. Background

The heart of a comet is the nucleus. The Halley probes suggest that cometary nuclei consist of dust with water ice throughout the dust. In addition molecules are trapped in the ice's crystalline structure.

As a comet approaches the sun the ice sublimates releasing the dust and trapped molecules forming an expanding cloud of material, the coma. Solar photons quickly dissociate the freed molecules forming daughter molecules. The molecular species observed in cometary spectra, such as OH, CN, C_3 , C_2 , NH, and NH_2 , are the disassociated products of the original trapped molecules. The molecules are eventually broken down into their atomic constituents and diffuse into space.

The atoms, molecules, and dust in the coma produce the observed cometary spectral features. Sunlight scattered by dust produces continuum radiation. Solar photons excite atoms and molecules that subsequently reradiate resulting in emission lines, i.e., the process of resonance fluorescence produces the emission lines.

The cometary spectrum at optical wavelengths varies a great deal from comet to comet and with heliocentric distance for a given comet. For example, the relative strength of continuum and emission line radiation varies from comet to comet and is an indication of the amount of dust released by the nucleus. Furthermore, emission line features for a given comet vary with heliocentric distance. At heliocentric distances of 1 AU molecular emission dominates. Comets with smaller heliocentric distances, 0.1 AU, have their spectra dominated by metals

and reflected solar continuum. Comet Halley spectra (see fig. 23) taken at a heliocentric distance of 0.9 AU shows C_2 to be the dominant optical emission feature.

Figure 1 shows the electronic energy level diagram for C_2 . The ten states shown are electronic states. The energy separation between electronic states is typically on the order of several electron volts (ev). Each electronic state has vibrational levels associated with it. The separation between vibrational levels within an electronic state is typically 0.1 ev. Electronic states a, b, c, d, and e are triplet states, i.e., spins are parallel. Electronic states X, A, C, D, and E are singlet states, i.e., spins are antiparallel. Note the ground state triplet has an energy higher than the ground state singlet.

Figure 1 also diagrams the dominant transitions seen in cometary C_2 . Transitions between triplet and singlet states have not been seen yet. Notice the absence of vibrational transitions within an electronic state. For radiation to interact with an atomic, molecular, or nuclear system's motions a mechanism must be supplied. The mechanism is a change in the electronic or magnetic property of the system as a result of the motion. In particular if a molecule has an electric dipole moment that oscillates as a result of vibrations, that vibrating dipole can interact with incident radiation producing an absorption or emission. Thus, molecules without electric dipole moments, such as C_2 , will not be able to have pure electric dipole vibrational transitions. Also, triplet-singlet electronic transitions are electric dipole forbidden, arguing for an independent consideration of singlet and triplet states.

There are no selection rules for Δv when C_2 makes an electronic transition. The quantity Δv is the difference in vibrational quantum number. In particular $v = v' - v''$ where v' is the vibrational quantum number in the upper electronic state and v'' is the vibrational quantum number in the lower electronic state. Thus a great many transitions are possible. In the discussion presented here transitions and associated spectral features will be grouped into two categories, bands and band sequences. Bands refer to transitions from an electronic and associated vibrational state to another electronic and associated vibrational state. Band sequences describe a set of transitions all having the same electronic transition and all having the same difference in vibrational quantum number. (See fig. 2)

For two decades active observational and theoretical research have attempted to describe C_2 's transitions and energy level populations. Theoretical research begins by deciding which electronic and vibrational states will be included in the calculations. Transition rates between the states are obtained from theory or obtained from laboratory data. The states and transition rates are combined in the equations of statistical equilibrium. An equation is written for each level. The equation for a level demands the number of transitions into a level equal the number of transitions out of a level. The equations for the levels are solved simultaneously resulting in a determination of the relative population distribution of C_2 among its states. The relative population distribution allows a Boltzman vibrational temperature, T_{vIB} , to be determined for the vibrational levels within an electronic state. The vibrational temperature is not a thermal temperature, but

merely a single parameter describing the vibrational level population within an electronic state. In addition the relative population distribution allows the band sequence flux ratios to be calculated. Observational research measures the cometary energy distribution over wavelength and then calculates the band sequence flux ratios. The Swan band fluxes $\Delta v=+1$, $\Delta v=0$, $\Delta v=-1$ are the most intense and hence the most frequently observed. Interaction between theoretical and observational determinations of vibrational temperatures and band sequence flux ratios over the last twenty years has led to more complex and accurate descriptions of C_2 .

Stockhausen and Osterbrock (1965) elaborated on an observational and theoretical discrepancy in cometary C_2 . They built a two electronic state model for the triplet states responsible for the Swan bands, each state having five vibrational levels. Stockhausen and Osterbrock showed the lowest triplet state should have a vibrational excitation temperature equal to the effective temperature of the sun, 5730 °K, if transitions between vibrational levels within an electronic state did not occur. Best observations at the time indicated a temperature of 2000 - 3000 °K. In response to this discrepancy Stockhausen and Osterbrock included pure magnetic dipole vibrational transitions as a mechanism for lowering the vibrational temperature. In their paper they estimated the magnetic dipole transition rate and then calculated the vibrational level populations and temperatures. The result was a satisfactory agreement between theory and observation.

Mayer and O'Dell (1968) concurred with arguments that Stockhausen and Osterbrock had overestimated the magnetic dipole transition rates,

casting suspicion on the mechanism. Mayer and O'Dell calculated the Swan band sequence flux ratios $F(\Delta v=+1)/F(\Delta v=0)$ and $F(\Delta v=-1)/F(\Delta v=0)$ dependence on vibrational temperature and compared the calculated ratios with photoelectrically observed ratios from Comet Rudnicki. They concluded $T_{VIB} = 4000 \text{ }^{\circ}\text{K}$. The more accurate determination of T_{VIB} was still far below the best theoretical prediction, $T_{VIB} = 5770 \text{ }^{\circ}\text{K}$.

Gebel (1970) observed Comets 1967n, 1968b, and 1968c and found $F(\Delta v=+1)/F(\Delta v=0)$ not to vary with heliocentric distance. This finding provides evidence against magnetic dipole vibrational transitions within an electronic state. Population by fluorescence would vary as $1/r^2$ and depopulation by magnetic dipole transitions would be constant with heliocentric distance. The resulting population variation would produce strongly varying band sequence flux ratios.

O'Dell (1971) noticed the constancy of $F(\Delta v=+1)/F(\Delta v=0)$ from comet to comet and ruled out collisional depopulation since the comets observed had large variations in density. The paper suggests the theoretical and observational discrepancy results from non inclusion of the Ballik-Ramsay bands in the calculations. (See fig. 1.)

To investigate the effect of non-inclusion of the Ballik-Ramsay bands Krishna Swamy and O'Dell (1977) constructed a statistical equilibrium model with the four lowest triplet electronic states, each having fourteen vibrational levels. The calculations provided a new depopulation mechanism. Diatomic carbon molecules in the higher vibrational levels of electronic state a can make electric dipole transitions to electronic state b followed by electric dipole transitions to the lower vibrational levels of electronic state a. The whole

process mimics a purely vibrational transition. Krishna Swamy and O'Dell calculate the band sequence flux ratios $\log[F(\Delta v=+1)/F(\Delta v=0)]$ and $\log[F(\Delta v=-1)/F(\Delta v=0)]$ obtaining -0.303 and -0.355 (1AU) respectively. The observational averages quoted from the paper are -0.297 ± 0.007 and -0.307 ± 0.015 . The remaining discrepancy is suggested to result from non-inclusion of triplet-singlet transitions, previously ignored.

II. Telescope/Spectrophotometer

The objective of the research program undertaken by the author was to obtain highly accurate measurements of cometary band and band sequence flux ratios for comparison with the latest and most elaborate C_2 model (Krishna Swamy and O'Dell 1986). The discussion to follow describes the telescope and detector used to obtain accurate measurements of the band and band sequence fluxes.

Periodic Comets Giacobini-Zinner, G-Z, and Halley were observed from the Cerro Tololo Inter-American Observatory, Chile. The Cerro Tololo site was selected because its -30° latitude made Comet Halley (Dec. = -20°) more accessible than Kitt Peak during the time worldwide coordinated observations were being made, in early March, 1986. The G-Z observations made in September, 1985 served to test the observing and reduction procedures to be used on Halley.

The 1-5 meter telescope with Harvard Scanner was used on both occasions. The scanner is a dual channel, low resolution, photo-electric, spectrophotometer. Predicted Halley brightness and dark time presented no conflict with the scanner's slowness, i.e., lower quantum efficiency relative to more modern detectors. In fact the accuracy desired ($>5\%$) and wide scanning interval desired (3000 - 10,000 Å) made it a good choice.

Figure 3 is a schematic diagram showing the Harvard Scanner's optical components. A focused image from the telescope's secondary mirror is produced at the Scanner's entrance aperture. Sorting filters behind the entrance aperture remove the overlap of spectral orders at

the exit slot. A collimator mirror produces a beam of parallel rays. The parallel rays are dispersed by the grating and the camera mirror produces a focused monochromatic image at the exit slot. The monochromatic image's intensity is measured by a photomultiplier tube, PMT, behind the exit slot.

In scanning the mode, the grating is rotated (stepped), causing the spectrum of monochromatic images to step in front of the exit slot and photomultiplier tube. The grating motion and resulting spectral motion at the slot is computer controlled. The observer enters scanning parameters such as wavelength range to be scanned in angstroms, step size in angstroms, and integration time in seconds. The output is displayed on a CRT. Scanning parameters and counts corresponding to each wavelength in the interval are displayed.

It was mentioned above that the scanner has two channels. These channels are separated by 2.9 arc minutes. The two channels make possible simultaneous sky and object measurements, reducing the effect of changing sky conditions. Comets G-Z and Halley, being extended objects, contaminated the sky channel and prohibited simultaneous sky comet observations. A single channel was used on both runs, the telescope being moved between the object and an adjacent area of sky showing no comet signal.

A variety of entrance apertures, filters, exit slots, and photomultiplier tubes accompany the scanner. A 1.378 mm diameter circular entrance aperture and a 1.219 mm x 10.000 mm rectangular exit slot were used during both observing runs. The combination produces a 40 Å bandpass in the second order. The large bandpass is sufficient for

studying the broad C_2 band sequences investigated here.

The blocking filters and photomultiplier tubes were selected to cover the spectrum from 3000 Å - 10,000 Å. The C_2 band sequences, the OH bands at 3085, and the CN band at 9180 were of primary interest. The later two bands were observed to link the observations made here with ultraviolet and infrared observations made at other sites during the March, 1986 onslaught.

Figure 4 shows how the 3000 Å - 10,000 Å interval was broken up into five configurations. Each configuration corresponds to a different tube filter combination. Executing a configuration caused the grating to step through the wavelength interval in the order shown.

The grating's blaze, 7500 Å in the first order, determined the wavelengths covered in each order. Shortward of 5800 Å measurements were made in the second order. Longward of 5000 Å measurements were made in the first order. The wavelength interval between 5000 Å and 5800 Å was measured in both orders. Filters for a configuration were selected to isolate the associated wavelength interval from overlapping wavelengths in other orders.

Photomultiplier tubes were selected to give the largest and best behaved quantum efficiencies over the 3000 - 10,000 Å interval. Figure 5 shows the quantum efficiency curves for the S-20 and S-1 tubes. Shortward of 7000 Å the S-20 tube has a higher quantum efficiency than the S-1 tube. From 7000 Å - 9000 Å the S-1 tube has a lower but less varying quantum efficiency curve than the S-20 tube. Greater than 9000 Å the S-1 tube has a higher and better behaved quantum efficiency curve than the S-20 tube. The interval from 5000 Å - 7000 Å was covered

by both the S-20 and S-1 tubes.

Correcting zero point errors in the scanner's wavelength scale was performed with a Hg lamp before the first night's observations. The telescope and Hg lamp were pointed at a screen on the dome and scanning executed. Comparing tabulated Hg line positions and intensities with scanner indicated line spacings and intensities called for a $34 \text{ \AA}$ scale correction. In addition, after Hg lamp calibrations on the first night and before program object observations on all nights, an A type star was scanned. The A star's strong Balmer lines were found at the correct wavelengths each night. After the initial $34 \text{ \AA}$ scale correction no further corrections were made.

III. Observations

The observational program for Giacobini-Zinner and Halley is described below. Each night's observations included standard star and cometary observations. A standard star being defined as a star having its relative absolute flux distribution known. The necessity of standard star observations results from the need to determine functions of wavelength, atmospheric extinction and instrument sensitivity, before cometary signal can be converted to an energy flux.

Atmospheric extinction will be divided into three components, ozone absorption, Rayleigh scattering, and dust scattering. A relation between a star's magnitude per unit wavelength interval above the atmosphere, $m_{\lambda,o,s}$, the star's magnitude per unit wavelength interval in the atmosphere, $m_{\lambda,s}$, and the magnitudes of atmospheric extinction per unit wavelength interval, $(k_{\lambda})(\text{airmasses})$, can be written as (1).

$$m_{\lambda,s} = (k_{\lambda})(\text{airmasses}) + m_{\lambda,o,s} \quad (1)$$

$$k_{\lambda} = k_o + k_R + k_d \quad (2)$$

The term k_{λ} is the extinction coefficient having units of magnitudes extincted per unit airmass per unit wavelength interval. One airmass is defined as the atmospheric layer lying between the observer and his zenith. Using this definition for one airmass we write airmasses = $\sec(z)$ where z is the zenith angle (figure 6). The expression airmass = $\sec(z)$ is valid for a plane parallel atmosphere. The plane parallel

atmosphere approximation is valid for the airmasses encountered during the G-Z and Halley runs. From (1) it is seen that observing a star's magnitude at a wide range of airmasses gives the extinction function, k_λ .

Although extinction can be determined by observing the signal change with airmass for any object, standard stars are usually used because by observing standard stars the system's sensitivity function can be obtained simultaneously. The sensitivity function can be written as

$$S_\lambda = N_{\lambda,s} / F_{\lambda,s} \Delta\lambda \frac{\pi D^2}{4} \quad (3)$$

where S_λ has units of counts per photon, $N_{\lambda,s}$ are counts received from the standard star corrected for atmospheric extinction, $F_{\lambda,s}$ is the standard star photon flux per unit wavelength interval, $\Delta\lambda$ is the bandpass, and $\frac{\pi D^2}{4}$ the telescope collecting area. Determining S_λ requires that $F_{\lambda,s}$ be known, i.e., a standard star is required. The sensitivity is intrinsic to the scanner. The sensitivity at a given wavelength gives the number of counts output for each photon input at that wavelength by the standard star. The sensitivity function's dependence on wavelength reflects the PMT's quantum efficiency curve, the sorting filter's transmission curve, the grating's blaze, and the telescope mirrors' reflectivities.

Standard stars were selected from Bregar's catalog (1976). The catalog contains 937 stellar energy distributions listed in magnitudes per unit frequency interval over a range from 3200 Å to 12,000 Å. The

data has been collected from many observers and converted to the α Lyrae flux system (Hayes and Latham 1975).

Comets Giacobini-Zinner and Halley being morning objects at the time observed limited the standard stars to those with right ascensions several hours west of each Comet, standards only an hour or two west of each Comet being preferred. The shorter interval between the standard star observation and the comet observation reduces the temporal variation in extinction.

Instrumental constraints and scientific objectives further reduced the number of standard star candidates. First, the stars needed to have their flux distributions over the 3300 Å - 10,000 Å interval for sensitivity function determination. Second, the stars were not to produce more than 100,000 counts per second. The scanner uses pulse counting electronics. A single photoelectron ejected from the photocathode moves through a chain of dynodes producing an avalanche of electrons. The avalanche of electrons forms a pulse. The time required to count the pulse produces a dead time. If a second pulse arrives during the time the first pulse is being counted, the second pulse will not be identified. Therefore, stars fainter than $m_v = 4.3$ were used. Last, the spectral energy distributions were required to be nearly linear from 3000 Å to 3400 Å. A linear extrapolation from the shortest Bregar listed magnitude, 3300 Å, to 3000 Å was made. Model atmospheres calculated by Kurucz (1979) encouraged use of the extrapolation in B, A, and F stars. Table 1 lists the standard stars used along with their right ascension, declination, visual magnitude, and spectral type.

TABLE 1
Standard Stars

Standard	R.A.	Dec.	Spec.	V
29 Psc	23h 59m 16s	-03D 18' 21''	B8III	5.1
45 Tau	04h 08m 40s	+05D 23' 40''	F4V	5.7
49 Tau	04h 12m 49s	+08D 46' 07''	B3V	4.3
θ Vir	13h 07m 22s	-05D 16' 21''	FOV	4.8
σ Ser	16h 19m 32s	+01D 08' 42''	A1V	4.5

After checking the wavelength scale zeroing with an A type star, dark signal and sky signal were measured. Typical sky signal was found to be 1-2% of the standard star signal during the G-Z run. During the Halley run dark signal dominated sky signal, the dark signal producing 4-7 counts per second. A full moon during the G-Z run and a new moon during the Halley run accounts for the difference in sky signal.

Which object to observe at what time and for precisely how long was determined by plotting each object's $\sec(z)$ vs local time. Figure 7 shows standard star and cometary $\sec(z)$ as a function of local time. Larger $\sec(z)$ or larger airmasses correspond to an object just appearing over the horizon. A $\sec(z)$ of one corresponds to an object at the observer's zenith. Thus the curves correspond to an object rising, reaching its zenith, and setting. The first standard star could be placed in the entrance aperture when its zenith angle was within the telescope's zenith angle range, $\sec(z) \leq 2.3$. The telescope's zenith angle range was set by a catwalk going around the dome, the telescope's aperture being obstructed by the catwalk if $\sec(z) > 2.3$. Scanning was

then executed. Each configuration was executed in turn. Once all the configurations had been executed they were repeated again and again until the next standard star was within the telescope's zenith angle range. The procedure just outlined was then repeated with the new standard star.

From figure 7 it is seen an object's airmass changes most quickly as the object rises. From (1) it is seen a wide airmass sampling is needed to determine the extinction function accurately. Thus observations as the standard star rises are of utmost importance.

Giacobini-Zinner was observed on the mornings of September 30 and October 1 with an S-20 tube. Giacobini-Zinner appeared as a faint smudge. It had no visible tail. Its faintness, $m = 8.7$, made it difficult to locate and track. Configuration 1 was executed with 20 Å step size and a 4 sec per channel integration time. The raw data clearly showed the OH and CN bands. Configuration 2 was executed with a 20 Å step size and an integration time up to 20 seconds per channel. The C_2 band sequences were not visible in the raw data. Sky observations were made after each comet observation, all observations occurring before the beginning of astronomical twilight.

Comet Halley was observed with an S-20 tube on March 12 and March 14. It was a naked eye object, $m = 4.5$. Dust and plasma tails were visible. Through the off axis guider it had a star like nuclear region and a roughly spherically symmetric coma. Acquisition was no problem and the starlike nucleus was used to guide on. Configurations 1, 2, and 3 had 2 sec per channel integration times. Configurations 1 and 2 had 20 Å step sizes. Configuration 3 had 40 Å step sizes. The 2 sec per

channel integration time was the smallest allowed by the scanner. The scanner could not be paused during the 2 sec integration scans. Thus guiding was checked and corrected between configurations. Each configuration was executed three or four times per night. The raw data showed OH, NH, CN, C₃, C₂, and NH₂ features. Sky observations were made in all configurations before Halley's zenith angle came into range. Once within range, Halley was observed in all configurations past the beginning of astronomical twilight. Halley observations were followed by more sky observations. The later sky measurements included good determination of solar and atmospheric absorption lines in all configurations.

The S-1 tube was used on March 13. Integration times, guiding procedure, and sky measurements were as described for the S-20 Halley observations. A step size of 40 Å was used. Configurations 4 and 5 showed NH₂ and CN features.

Halley sky measurements were treated in the manner described because it was available for half the time G-Z was available. Halley was available for one hour each night. Telescope movement between comet and sky after each configuration was avoided, saving time. The dominance of the dark signal over the sky signal supported use of the method. Dark signal was typically 1% of the comet signal for S-20 observations. Dark signal was typically 5% of comet signal for S-1 observations.

The principal difficulties associated with observing Comets Giacobini-Zinner and Halley was the limited observing time and accurate guiding. Observing time was limited by the maximum zenith angle allowed

by the telescope and by the brightening sky. The second difficulty, accurate guiding, results from the telescope's sidereal tracking rate and the comet's non sidereal motion. Maintaining each comet's centering in the scanner's entrance aperture was accomplished by the use of short scans and frequent checks and corrections by eye with the through-the-slit viewer (see figure 3). Guiding was accurate to a few arc seconds. It was also possible to "tweak" the right ascension and declination tracking rates on the 1-5 m; however, there was no noticeable increase in guiding accuracy.

IV. Reduction

The objective of the data reduction procedure described below is determination of the flux emitted from molecular bands and band sequences. Hence, the cometary flux in $\text{ergs cm}^{-2} \text{s}^{-1} \text{\AA}^{-1}$ is to be calculated at each wavelength cometary signal has been measured. Figure 8 diagrams the reduction process. The reduction process can be divided into standard star calculations and cometary calculations, i.e., the two columns in figure 8. Extinction and sensitivity functions are the results of the standard star calculations. These functions are then used in the cometary calculations.

From figure 8 it is seen the first step in determining cometary flux is calculation of extinction coefficients from the standard star observations. Replacing airmasses with $\sec(z)$ in (1) we have

$$m_{z,\lambda} = k_{\lambda} \sec(z) + m_{0,\lambda} \quad (4)$$

We can write a relation between standard star counts received above the atmosphere and standard star photon flux

$$N_{\lambda} = F_{\lambda} S_{\lambda} \Delta\lambda \frac{\pi D^2}{4} t \quad (5)$$

N_{λ} are counts above the atmosphere, F_{λ} is the standard star photon flux in $\text{photons cm}^{-2} \text{s}^{-1} \text{\AA}^{-1}$, S_{λ} is the sensitivity in counts per photon, $\Delta\lambda$ is the bandpass in angstroms, D is the telescope diameter in centimeters, and t is the integration time in seconds. The raw standard

star counts output from the scanner can be written as

$$n_{z,\lambda} = f_{\lambda} S_{\lambda} \Delta\lambda \frac{\pi D^2}{4} \quad (6)$$

where $n_{z,\lambda}$ are standard star counts output from the scanner with the telescope at zenith angle z , and f_{λ} is the photon flux incident upon the telescope. Magnitudes in (4) are related to fluxes in (5) and (6) by

$$m = -2.5 \log(\text{flux}) + c \quad (7)$$

Combining (4), (5), (6), and (7) results in (8).

$$-2.5 \log n_{z,\lambda} = k_{\lambda} \sec(z) - 2.5 \log N_{\lambda} \quad (8)$$

From plots of $-2.5 \log n_{z,\lambda}$ vs $\sec(z)$ for a particular wavelength, standard star, and night a value for k_{λ} is obtained from the slope. Not only does each standard star produce a determination of the extinction coefficients, but also the comet signal can be substituted into (8) to determine k_{λ} . Figure 9 shows (8) plotted for 5000 Å using σ Ser θ Vir, and Comet Halley.

For the sake of organization and clarity, in what follows observations will be referred to by night number. For example, observations made on the evening of March 10 through the morning of March 11 will be designated as night 1 observations. Similarly, observations made on the evening of March 13 through the morning of March 14 will be designated as night 4 observations.

The wide airmass range sampled on the Halley standards allowed a good determination of the extinction coefficients. The extinction coefficients were calculated at wavelengths free from atmospheric and stellar absorption lines, i.e., wavelengths corresponding to magnitudes tabulated in the Bregar catalog. The extinction coefficients were determined from observations made on nights 2, 3, and 4. Night 2 was cloudy early in the evening, hindering standard star observations. In particular, only configuration 2 on night 2 provided usable data for extinction determinations. However, the sky on night 2 cleared in time for Comet observations. Night 3 also had a cloudy interval during the σ Ser observations. Only θ Vir data from night 3 was usable for extinction determination. Again, the sky cleared in time for Halley observations. Night 4 had no clouds. The extinction coefficients determined from each standard star and the Comet were averaged. The average was weighted according to the number of points determining (8) and the airmass range of the points. Table 2 lists the average extinction coefficients calculated for the Halley run. The third column gives the standard deviations, s .

TABLE 2

Avg. Extinction Coefficients for the Halley Run
(magnitudes/airmass)

$\lambda, \text{\AA}$	k_{λ}	s
3200	1.05	0.18
3500	0.58	0.20
4460	0.36	0.09
5000	0.31	0.06
5540	0.26	0.06

For the Halley run an extinction coefficient function was determined for $\lambda \geq 3200 \text{ \AA}$. Referring to (2) and realizing ozone absorption and Rayleigh scattering are negligible relative to dust scattering at near infrared wavelengths the gray extinction component was determined, i.e., $k_\lambda = k_e$. Table 3 gives the result of slopes from (8) using θ Vir data taken on night 3. Again, the other standard, σ Ser, observed on night 3 was clouded out. Halley was not used in determining the coefficients due to the fewer counts, 100X fewer, resulting in an ill-defined k_λ .

TABLE 3
Extinction Coefficients for the Halley Run
(magnitudes/airmass)

$\lambda, \text{ \AA}$	k_λ
8400	0.04
8820	0.07
9700	0.08
9940	0.03

The average being $k_e = 0.06 \pm 0.02$. Equation (2) can be written as

$$(k_\lambda - k_e) = R\lambda^{-4} \quad (9)$$

or using logs

$$\log (k_\lambda - k_e) = \log R - 4 \log \lambda \quad (10)$$

The Rayleigh component in (9) can be determined by plotting $\log(k_\lambda - k_0)$ vs $\log \lambda$ and using $k_0 = 0.06$ and the Table 2 data. Fitting a line to the data with a slope equal to -4 yields $\log R$ and thus R . Figure 10 shows the fit. The result is

$$k_\lambda = 0.06 + \frac{1.17 \times 10^{-14}}{\lambda^4} \quad (11)$$

where λ is in angstroms. Equation (11) is valid for $\lambda \geq 3200 \text{ \AA}$. For $\lambda \leq 3200 \text{ \AA}$ the extinction coefficients were calculated from standard star data and (8) at each wavelength step. Table 4 shows the results for night 4. As noted above, early clouds hindered extinction determination on night 2. Halley was not used due to the small signal received and the resulting ill-defined k_λ .

TABLE 4

Extinction Coefficients for the Halley Run
(magnitudes/airmass)

$\lambda, \text{ \AA}$	$\theta \text{ Vir}$	$\sigma \text{ Ser}$	Avg
3040	2.81	2.42	2.62
3060	2.42	2.11	2.24
3080	2.29	1.72	1.96
3100	1.96	1.45	1.67
3120	1.76	1.35	1.53
3140	1.65	1.27	1.43
3160	1.45	1.20	1.31
3180	1.38	1.11	1.23
3200	1.29	0.97	1.11

Figure 11 shows the extinction coefficients determined for the Halley run along with Stone and Baldwin's (1983) determination of CTIO extinction coefficients.

The airmass ranges for the G-Z standards were not great enough to determine the extinction coefficients better than Stone and Baldwin. The extinction function was determined by fitting a curve graphically to the Stone and Baldwin data, figure 12. For wavelengths shorter than 3200 Å Stone and Baldwin do not list extinction coefficients. Thus 29 Psc and 49 Tau data was used to determine the coefficients. Table 5 gives the results.

TABLE 5
Extinction Coefficients for the G-Z Run
(magnitudes/airmass)

λ , Å	49 Tau (4)	29 Psc (3)	49 Tau (3)	Avg	s
3060	2.21	2.39	2.50	2.45	0.08
3080	1.76	1.95	2.02	1.99	0.05
3100	1.68	1.87	1.66	1.77	0.15
3120	1.59	1.45	1.57	1.51	0.08
3140	1.29	1.42	1.40	1.41	0.01
3160	1.09	1.26	1.22	1.24	0.03
3180	1.20	1.17	1.13	1.15	0.03
3200	1.01	1.12	1.01	1.07	0.08

The number in parenthesis designates the night.

Again referring to figure 8 it can be seen the next step after obtaining the extinction coefficients is to correct the standard star

signal for extinction. Rewriting (8) we obtain

$$\log N_{\lambda} = \log n_{z,\lambda} + 0.4 \bar{k}_{\lambda} \sec(z) \quad (12)$$

Thus $\log N_{\lambda}$ can be calculated with knowledge of $\bar{k}_{\lambda}$.

Figure 8 now indicates standard star data corrected for atmospheric extinction combined with standard star fluxes allows the sensitivity to be calculated. The sensitivity was given by (3)

$$S_{\lambda} = N_{\lambda,s} / F_{\lambda,s} \Delta\lambda \frac{\pi D^2}{4} \quad (3)$$

and can be rewritten with logs as equation (13).

$$\log S_{\lambda} = \log N_{\lambda,s} - \log F_{\lambda,s} - \log \left(\Delta\lambda \frac{\pi D^2}{4} \right) \quad (13)$$

The last term in (13) is irrelevant for determining comet flux. Furthermore, since the telescope diameter is not accurately known the last term in (13) will be dropped. That the term is irrelevant can be seen as follows. The cometary photon flux can be written as

$$F_{\lambda,c} = N_{\lambda,c} / S_{\lambda} \Delta\lambda \frac{\pi D^2}{4} \quad (14)$$

where $F_{\lambda,c}$ is the flux in photons $\text{cm}^{-2} \text{s}^{-1} \text{\AA}^{-1}$, and $N_{\lambda,c}$ are the counts recorded above the atmosphere. Again using logs (14) can be written as (15).

$$\log F_{\lambda,c} = \log N_{\lambda,c} - \log S_{\lambda} - \log \left(\Delta\lambda \frac{\pi D^2}{4} \right) \quad (15)$$

Combining (13) and (15) results in (16)

$$\log F_{\lambda,c} = \log N_{\lambda,c} - [\log N_{\lambda,s} - \log F_{\lambda,s}] \quad (16)$$

The bandpass, $\Delta\lambda$ and the telescope diameter, D , do not appear in (16). Thus, the quantity in brackets is of interest.

$$\log S_{\lambda} = [\log N_{\lambda,s} - \log F_{\lambda,s}] \quad (17)$$

Combining (12) and (17) results in (18)

$$\log S_{\lambda} = [\log n_{\lambda,z} + 0.4k_{\lambda} \sec(z) - \log F_{\lambda,s}] \quad (18)$$

To determine (18) $F_{\lambda,s}$ must be determined. The Bregar catalog tabulates wavelengths and associated magnitudes per unit frequency interval while (18) requires photon flux in photons $\text{cm}^{-2} \text{s}^{-1} \text{\AA}^{-1}$. The conversion was made as follows. Consider first a relation between the magnitude per unit frequency interval and flux ($\text{ergs cm}^{-2} \text{s}^{-1} \text{Hz}^{-1}$) at two different frequencies for a star in the Bregar catalog.

$$m_{B,v} - m_{B,5445} = 2.5 \log \frac{f_{B,5445}}{f_{B,v}} \quad (19)$$

Rewriting (19) as (20)

$$\log f_{B,v} = \log f_{B,5445} - 0.4(m_{B,v} - m_{B,5445}) \quad (20)$$

Consider now two stars, one α Lyrae the other the Bregar star. We can write a relation between the visual magnitudes and the associated fluxes ($\text{ergs cm}^{-2} \text{ s}^{-1} \text{ \AA}^{-1}$).

$$V_B - V_L = 2.5 \log \frac{f_{L,5445}}{f_{B,5445}} \quad (21)$$

$$\log f_{B,5445} = \log f_{L,5445} - 0.4(V_B - V_L) \quad (22)$$

Combining (20) and (22) yields (23).

$$f_{B,v} = 10^{0.4V_L} f_{L,5445} \text{ dex}[-0.4(V_B + m_{B,v} - m_{B,5445})] \quad (23)$$

Hays and Latham (1975) give $V_L = +0.04$ and from their energy distribution for α Lyrae $f_{L,5445} = 3.562 \times 10^{-20} \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ Hz}^{-1}$. Thus we obtain (24).

$$f_{B,v} = 3.674 \times 10^{-20} \text{ dex}[-0.4(V_B + m_{v,B} - m_{B,5445})] \quad (24)$$

where $f_{B,v}$ is in $\text{ergs cm}^{-2} \text{ s}^{-1} \text{ Hz}^{-1}$. Also, we have (25) and (26).

$$f_v \frac{c}{\lambda^2} = F'_\lambda \quad (25)$$

$$F_\lambda = F'_\lambda \frac{\lambda}{hc} \quad (26)$$

where F'_λ is in $\text{ergs cm}^{-2} \text{ s}^{-1} \text{ \AA}^{-1}$.

Combining (25) and (26) yields (27).

$$F_{\lambda} = 1.509 \times 10^{26} \frac{f\nu}{\lambda} \quad (27)$$

Equations (24) and (27) then give the standard star flux in photons $\text{cm}^{-2} \text{s}^{-1} \text{\AA}^{-1}$.

The standard stars used on both runs had magnitudes listed for wavelengths as short as 3300 $\text{\AA}$. To obtain values of $F_{\lambda,s}$ shorter than 3300 $\text{\AA}$ required extrapolation. Figure 13 shows a plot of standard star energy flux, f_{ν} , in $\text{ergs cm}^{-2} \text{s}^{-1} \text{Hz}^{-1}$ vs wavelength in angstroms. The plot and Kurucz (1979) support a linear extrapolation down to 3040 $\text{\AA}$. The extrapolation was performed with a HP-15C hand calculator and used fluxes between 3300 $\text{\AA}$ and 3620 $\text{\AA}$ as the basis for the extrapolation.

Using raw standard star counts, $n_{z,\lambda}$, $\sec(z)$, $\bar{k}_{\lambda}$, and (18) allowed $\log(S_{\lambda})$ to be calculated at standard star wavelengths. Night 4 provided the majority of $\log(S_{\lambda})$ data for configurations 1, 2 and 3. Ten usable executions of configuration 1 resulted in ten determinations of $\log(S_{\lambda})$ for each standard star wavelength in configuration 1. Configuration 2 had eight determinations of $\log(S_{\lambda})$ for each standard star wavelength and configuration 3 had seven determinations of $\log(S_{\lambda})$. Night 2 provided only two determinations of $\log(S_{\lambda})$ for wavelengths in configuration 2. The excellent agreement between $\log(S_{\lambda})$ on night 2 and night 4 suggested using sensitivities determined on night 4, on night 2 as well. However, the night 2 configuration 2 $\log(S_{\lambda})$ data were used in night 2 calculations. Night 3 had one and three usable executions of configurations 4 and 5 respectively; the

standard 0 Vir being the object scanned. The average and one standard deviation of the $\log(S_\lambda)$ measurements were calculated for each wavelength for each night. The averages and their standard deviations were plotted on a $\overline{\log(S_\lambda)}$ vs wavelength axes for each configuration. Curves were fit to the points, producing $\overline{\log(S_\lambda)}$ for each step in the configurations. Figures 14-20 show the curves.

Referring to figure 8, it is seen the next step is to correct comet data for atmospheric extinction. Specifically,

$$\log N_{\lambda,c} = \log n_{z,\lambda,c} + 0.4 \bar{k}_\lambda \sec(z) \quad (28)$$

$n_{z,\lambda,c}$ is comet signal with the telescope at zenith angle z . Equation (28) is evaluated at each wavelength step. The extinction coefficients are taken from table 4 and (11) for Halley observations and table 5 and figure 12 for G-Z observations.

Using $\log F_{\lambda,c} = \log N_{\lambda,c} - \overline{\log S_\lambda}$, (28), figures 14-18 for Halley observations, and figures 19, 20 for G-Z observations allowed photon flux, $F_{\lambda,c}$, in photons $\text{cm}^{-2} \text{s}^{-1} \text{\AA}^{-1}$ to be determined at each wavelength step. The conversion from photon flux to energy flux is made by (26)

$$F'_\lambda = F_{\lambda,c} \frac{hc}{\lambda} \quad (26)$$

where F'_λ has units of $\text{ergs cm}^{-2} \text{s}^{-1} \text{\AA}^{-1}$.

Calculation of cometary energy flux at each wavelength step in all the configurations was facilitated by use of programs executed on a Perkin-Elmer computer. A "C" program was written for each

configuration. A program read comet signal, extinction, and log (sensitivity) files; it executed (26), (28), and $\log F_{\lambda,c} = \log N_{\lambda,c} - \overline{\log S_{\lambda}}$ at each wavelength step; finally, the program wrote a file containing cometary energy flux at each wavelength step in the configuration. Figure 21 is the program executed for configuration 1 Halley observations.

Figures 22 through 26 show sample Halley spectra obtained from executing configurations 1-5 with a 2 sec per channel integration time on night 4. Figures 27 and 28 show G-Z spectra obtained from executing configuration 1 and configuration 2 with a 4 sec per channel and a 2 sec per channel integration time respectively. The G-Z spectra are for night 3. Configuration 1-5 were each performed several times during the hour Halley was available each night.

The final phase of the reduction process was to determine the fluxes emitted from molecular bands and band sequences. The emission features in figures 22-28 contain a small continuum contribution which must be subtracted. The flux emitted by a molecular band or band sequence is given by

$$F'_B = \sum_{\lambda} (F'_{\lambda,c} - F'_{\lambda,c,c}) \Delta\lambda' \quad (29)$$

where $F'_{\lambda,c,c}$ is the cometary continuum flux at wavelength step λ in ergs $\text{cm}^{-2} \text{ s}^{-1} \text{ \AA}^{-1}$. The term $\Delta\lambda'$ is the step size and the sum in (29) is over the wavelengths composing the band or band sequence. The continuum at each step within the band or band sequence, $F'_{\lambda,c,c}$, was determined by interpolating between the continuum on either side of the feature.

Several wavelengths steps on one side of a feature containing continuum signal only were averaged and several wavelength steps on the other side of a feature containing continuum signal only were averaged. The averages provided good values for the end points of the interpolation. A HP-15C's interpolation routine performed the calculations. Table 6 gives the specifics for the band and band sequence flux calculations.

TABLE 6

Parameters in Band and Band Sequence Calculations

Species	Interval Summed Over A	Intervals Continuum Averaged Over A	Absorption Line Corr.
OH	3060-3120	*3200-3320,	None
NH	3340-3380	3260-3320, 3400-3460	None
CN	3860-3920	3780-3840, 4120-4160	None
C2($\Delta v = 1$)	4480-4740	4400-4460, 4760-4820	None
C2($\Delta v = 0$)	4840-5180	4760-4820, 5220-5280	Solar
C2($\Delta v = -1$)	5300-5640	5220-5280, 5760-5800	None
CN(1 - 0)	9140-9220	9100 , 9260	Atm

* This continuum interval was used to extrapolate the cometary continuum to 3060-3120 A.

The last column in table 6, absorption line corrections, tells whether the band or band sequence had any hidden solar or atmospheric absorption lines coincident with the band or band sequences summing interval, column 2. The cometary continuum is produced from scattered solar radiation, hence, solar absorption lines in the solar continuum are present in the cometary continuum. Further, the atmospheric

extinction corrections did not include absorption by O₂ and H₂O bands in the near infrared. These atmospheric bands are seen to be superimposed on the Halley spectra.

To locate and determine the strength of these absorption lines, configurations 1-5 were executed with a bright sky in the entrance aperture at the end of each night's observations. The sky signal's magnitude was comparable to standard star signals. The sky flux in ergs cm⁻² s⁻¹ Å⁻¹ was calculated at each wavelength step as described in the cometary flux calculations. The raw sky signal and $\overline{\log(s_\lambda)}$ values at each wavelength step for a configuration were read into the configuration's "C" program. The program correcting for extinction and put the corrected signal on the α Lyrae flux system of Hayes and Latham. Figures 29-33 show the sky spectra taken on night 4 with a 2 sec per channel integration time. The spectra give the solar continuum with solar and atmospheric absorption lines superimposed. The cometary continuum was corrected by calculating the ratio X_λ from the solar spectra.

$$X_\lambda = \frac{F'_{\text{SOLAR},\lambda}}{F''_{\text{SOLAR},\lambda}} \quad (30)$$

In (30) $F'_{\text{SOLAR},\lambda}$ is the solar flux in ergs cm⁻² s⁻¹ Å⁻¹ at the wavelength step λ including solar and atmospheric O₂ and H₂O absorption and $F''_{\text{SOLAR},\lambda}$ is the solar flux at the same wavelength step if there were no absorption line present. Multiplying X_λ by $F'_{\lambda,c,c}$ gives the absorption line corrected value for the cometary continuum. This corrected value is then used in (29) to determine band sequence fluxes.

The quantity $F_{\text{SOLAR},\lambda}''$ was obtained by interpolating between the continuum flux on either side of the absorption features in figures 29-33. A HP-15C's interpolating routine performed the calculations. Table 6a gives X_λ for the wavelength steps corrected in configurations 1-5.

TABLE 6a

$\lambda, \text{\AA}$	X_λ
4840	0.97
4860	0.89
4880	0.96
5000	0.97
5020	0.93
5180	0.90
9140	0.99
9180	0.90
9220	1.10

Band and band sequences $C_2 \Delta v=-2$, $NH_2(0,8,0)$, $NH_2(0,7,0)$, and CN (3-0) in configuration 3 and configuration 4 were not calculated because they were contaminated either by other cometary emission lines, sky emission, or solar absorption lines. The $C_2 \Delta v=-2$ band sequence is contaminated by the $NH_2(0,9,0)$ band, the $NH_2(0,8,0)$ band is contaminated by [OI] night sky emission, and the $NH_2(0,7,0)$ band is contaminated by $H\alpha$, the solar absorption line in the cometary continuum. These features were of secondary importance here and attempts to calculate band or band sequence fluxes were not made.

Table 7 gives the band and band sequence fluxes calculated as

discussed above. The first column of the tables gives the universal time when the configuration was executed. Universal time, U.T., being measured relative to midnight at Greenwich, 0:00 U.T.

TABLE 7a

Night 2	Configuration 1 Band Fluxes ^a		
U.T.	OH	NH	CN
9:11	2279	140.0	1134
9:18	2191	163.3	1085
9:37	2236	140.6	1099

^ain ergs cm⁻²s⁻¹ x10¹²

TABLE 7b

Night 4	Configuration 1 Band Fluxes ^a		
U.T.	OH	NH	CN
8:49	4322	272.5	1762
8:55	4078	258.4	1660
9:21	3611	220.4	1535
9:26	4029	235.7	1619

^ain ergs cm⁻²s⁻¹ x10¹²

TABLE 7c

Night 2 U.T.	Configuration 2 Band Seq. Fluxes ^a		
	C ₂ Δv=+1	C ₂ Δv=0	C ₂ Δv=-1
8:52	665.5	1191	605.8
9:24	638.2	1172	614.4
9:31	658.2	1185	587.7

^ain ergs cm⁻²s⁻¹ x10¹²

TABLE 7d

Night 4 U.T.	Configuration 2 Band Seq. Fluxes ^a		
	C ₂ Δv=+1	C ₂ Δv=0	C ₂ Δv=-1
8:27	945.9	1707	868.2
8:33	951.5	1785	849.8
9:01	893.9	1651	855.4
9:08	953.1	1786	819.6

^ain ergs cm⁻²s⁻¹ x10¹²

TABLE 7e

Night 3 U.T.	Configuration 5 Band Fluxes ^a		
	CN (1,0)	8:58	176.5
9:07	131.2	9:15	201.9
9:32	180.8	9:40	151.9

^ain ergs cm⁻²s⁻¹ x10¹²

TABLE 7f

Night 3 G-Z Configuration 1 Band Fluxes ^a		
U.T.	OH	CN
7:06	*147.9	101.6

*Interpolated continuum between 3060 Å and 3160 Å.
^ain ergs cm⁻² s⁻¹ x10¹²

Table 8 lists C₂ band sequence flux ratios F(Δv=+1)/F(Δv=0) and F(Δv=-1)/F(Δv=0) and the log of these ratios.

TABLE 8a

Night 2		C ₂ Band Sequence Flux Ratios ^b		
U.T.	$\frac{F(\Delta v=+1)}{F(\Delta v=0)}$	$\frac{F(\Delta v=-1)}{F(\Delta v=0)}$	$\log\left(\frac{F(\Delta v=+1)}{F(\Delta v=0)}\right)$	$\log\left(\frac{F(\Delta v=-1)}{F(\Delta v=0)}\right)$
8:52	0.559	0.509	-0.253	-0.294
9:24	0.545	0.524	-0.264	-0.280
9:31	0.556	0.496	-0.255	-0.304

^bHeliocentric Distance, r = 0.87 AU
 Geocentric Distance, Δ = 1.01 AU

TABLE 8b

Night 4		C ₂ Band Sequence Flux Ratios ^c		
U.T.	$\frac{F(\Delta v=+1)}{F(\Delta v=0)}$	$\frac{F(\Delta v=-1)}{F(\Delta v=0)}$	$\log\left(\frac{F(\Delta v=+1)}{F(\Delta v=0)}\right)$	$\log\left(\frac{F(\Delta v=-1)}{F(\Delta v=0)}\right)$
8:27	0.554	0.509	-0.256	-0.293
8:33	0.533	0.476	-0.273	-0.322
9:01	0.541	0.518	-0.266	-0.286
9:08	0.534	0.459	-0.273	-0.338

^cHeliocentric Distance, $r = 0.90$ AU
 Geocentric Distance, $\Delta = 0.96$ AU

V. Results and Errors

The reduction section ended with the fluxes from the molecular band and band sequences, while in this section, band and band sequence fluxes are determined for each night. Also, errors in the band and band sequence fluxes are calculated.

The best way to see how errors can creep into the measurements is to combine (12), (16), and (28). The combination leads to (31).

$$\begin{aligned} \log F_{\lambda,c} = & \log n_{z,\lambda,c} - \log n_{z,\lambda,s} + \log F_{\lambda,s} + \\ & + 0.4 (\sec(Z_c) - \sec(Z_s)) \end{aligned} \quad (31)$$

The first term on the right side of (31), $n_{z,\lambda,c}$, has two possible sources of inaccuracy, photon noise and guiding imperfections. Photon noise is the statistical fluctuation of incoming photons from the object observed. In an ideal experiment inaccuracies from the experimental procedure and inaccuracies from the instrument are small in comparison to uncertainty due to photon noise. The second term on the right, $n_{z,\lambda,s}$, has its accuracy limited by photon noise since guiding was not a problem for standard star observations. The standard star signal, $n_{z,\lambda,s} \geq 10^4$, for most wavelength steps, suggests an accuracy of 1% for the standard star observations. The tabulated standard star fluxes are accurate to 1%. The k_λ term is the least accurately determined parameter in (31). Atmospheric extinction coefficients were determined from observations over different parts of the sky over several hours.

However, the standard star observations and comet observations were made over very similar zenith angles, $1.4 < \sec(z) < 2.3$. See figure 9. Hence, the extinction correction term in (31) is small and any error in the extinction coefficients has a minimal effect on determining the comet flux at a particular wavelength step. Thus, at the outset it is expected the accuracy of the band and band sequence measurements is primarily determined by cometary photon noise and guiding.

The photon noise to signal ratio is given by (32)

$$\frac{N}{S} = \frac{1}{n^{1/2}} \quad (32)$$

where n is the number of counts. The noise to signal ratio for a band or band sequence was determined by calculating the counts in a band or band sequence. Specifically,

$$n_B = \sum_{\lambda} (n_{z,\lambda,c} - n_{\text{CONT}}) \quad (33)$$

where $n_{z,\lambda,c}$ are the counts in wavelength step λ , n_{CONT} are the number of continuum counts in a wavelength step, and the sum is over the wavelength steps composing the band or band sequence. The noise to signal ratio was then calculated by (32).

For a given night there are multiple determinations of a band or band sequence flux. Hence, it is possible to calculate an accuracy based on the average and the dispersion of the band or band sequence fluxes for a given night. The accuracy being given by

$$A_{\text{DISP}} = \frac{(s/\sqrt{m})}{\overline{F}_B} \quad (34)$$

where s is the standard deviation of the band or band sequence determinations, m is the number of determinations, and $\overline{F}_B$ is the average of the band or band sequence determinations. Table 9 compares the accuracies determined from the photon noise and from the dispersion of band or band sequence fluxes on night 4.

TABLE 9

	$(\frac{N}{S}) \times 100$	$(A_{\text{DISP}}) \times 100$
OH	1.9%	3.7%
NH	2.3%	4.8%
CN(3885)	0.7%	2.9%
C2 $\Delta v = +1$	0.7%	1.5%
C2 $\Delta v = 0$	0.5%	1.9%
C2 $\Delta v = -1$	1.3%	1.3%
CN(9180)	6.8%	7.3%

Table 9 indicates the accuracies from the flux dispersions are close to those from photon noise. Imperfections in guiding most likely account for the difference in the two accuracies.

Table 10 gives the averages and errors for band fluxes and band sequence fluxes. The errors being calculated from $\frac{s}{\sqrt{m}}$.

TABLE 10

Halley Band and Band Sequence Fluxes ^a			
	Night 2	Night 3	Night 4
OH	2235 ± 25	--	4010 ± 148
NH	148 ± 7.7	--	247 ± 12
CN(3885)	106 ± 15	--	1644 ± 47
CN(9180)	-	168 ± 12	-
C ₂ (Δv=+1)	654 ± 8.2	--	936 ± 14
C ₂ (Δv=0)	1183 ± 5.6	--	1732 ± 33
C ₂ (Δv=-1)	603 ± 7.9	--	848 ± 10

^ain ergs cm⁻²s⁻¹ x10¹²

Table 11 gives the Swan band sequence flux ratios for night 2 and night 4 along with an error calculated from the dispersion.

TABLE 11

Halley Swan Band Sequence Flux Ratios		
	Night 2	Night 4
F(Δv=+1)/F(Δv=0)	0.553 ± 0.004	0.541 ± 0.005
F(Δv=-1)/F(Δv=0)	0.510 ± 0.008	0.491 ± 0.014

VI. Theory

At this point the G-Z and Halley observations have been described and the data reduction process discussed fully. The last section ended with the results obtained for Halley's C_2 band sequence ratios $F(C_2 \Delta v = +1)/F(C_2 \Delta v = 0)$ and $F(C_2 \Delta v = -1)/F(C_2 \Delta v = 0)$. In this section the theoretical calculations leading to the C_2 band sequence ratios are discussed in more detail. Also, the C_2 band sequence ratios obtained from Krishna Swamy and O'Dell's (1986) latest statistical equilibrium model are discussed.

The following model illustrates how vibrational level populations and temperatures are obtained from statistical equilibrium equations. The model also demonstrates that the vibrational temperature for C_2 's lowest triplet state should be equal to the effective temperature of the sun, as discussed by Stockhausen and Osterbrock (1965). Figure 34 shows the model's energy level diagram.

Figure 34

Levels 1 and 2 are vibrational levels belonging to C_2 's lowest electronic triplet state and level 3 is another triplet electronic state corresponding to an upper level of the Swan system. The equations of statistical equilibrium are

$$A_{31}^{A_{31}} + n_2 A_{21} + n_3 B_{31} \rho_{31} + n_2 B_{21} \rho_{21} = n_1 B_{12} \rho_{12} + n_1 B_{13} \rho_{13} \quad (35)$$

$$n_1 B_{23} \rho_{23} + n_3 B_{32} \rho_{32} + n_3 A_{32} = n_2 B_{23} \rho_{23} + n_2 A_{21} + n_2 B_{21} \rho_{21} \quad (36)$$

$$n_2 B_{23} \rho_{23} + n_1 B_{13} \rho_{13} = n_3 B_{31} \rho_{31} + n_3 B_{32} \rho_{32} + n_3 A_{31} + n_3 A_{32} \quad (37)$$

where n_i are the number of molecules per cm^3 in level i , ρ_{ij} is the radiation density in ergs cm^{-3} for photons with energy $h\nu_{ij}$. The energy density can be written as (38)

$$\rho_{ij} = \sigma_{ij} / (e^{h\nu_{ij}/kT} - 1) \quad (38)$$

$$\text{where } \sigma_{ij} = \frac{8\pi h \nu_{ij}^3}{c^3}$$

The terms A_{ji} , B_{ij} , B_{ji} , are the transition probabilities in sec^{-1} for spontaneous emission, absorption, and stimulated emission respectively. Previously it was seen C_2 does not have purely vibrational electric dipole transitions. We assume transitions between level 1 and 2 do not occur, i.e., $A_{ji} = B_{ij} = B_{ji} = 0$. In addition we set all stimulated transition rates equal to zero. This will be justified later. With

these transition rates set to zero and dividing (35), (36), and (37) by n_1 , (39), (40), and (41) result.

$$\frac{n_3}{n_1} A_{31} = B_{13} \rho_{13} \quad (39)$$

$$\frac{n_3}{n_1} A_{32} = \frac{n_2}{n_1} B_{23} \rho_{23} \quad (40)$$

$$\frac{n_2}{n_1} B_{23} \rho_{23} + B_{13} \rho_{13} = \frac{n_3}{n_1} A_{31} + \frac{n_3}{n_1} A_{32} \quad (41)$$

Rewriting (40) gives (42).

$$\frac{n_2}{n_1} = \frac{n_3}{n_1} \frac{A_{32}}{B_{23} \rho_{23}} \quad (42)$$

Combining (39) and (42) produces (43).

$$\frac{n_2}{n_1} = \frac{B_{13} \rho_{13}}{A_{31}} \frac{A_{32}}{B_{23} \rho_{23}} \quad (43)$$

The B_{ij} coefficient is related to the A_{ji} coefficient by (44).

$$B_{ij} = A_{ji} \frac{g_j}{g_i} \frac{1}{\sigma_{ij}} \quad (44)$$

where g_i and g_j are the statistical weight factors for states i and j .

Applying (44) to B_{13} and B_{23} , produces (45) and (46).

$$B_{13} = A_{31} \frac{g_3}{g_1} \frac{1}{\sigma_{13}} \quad (45)$$

$$B_{23} = A_{32} \frac{g_3}{g_2} \frac{1}{\sigma_{23}} \quad (46)$$

Combining (43), (45), and (46) gives (47).

$$\frac{n_2}{n_1} = \frac{g_2}{g_1} \frac{(e^{h\nu_{23}/kT} - 1)}{(e^{h\nu_{13}/kT} - 1)} \quad (47)$$

For optical photons and $T = 5770^\circ$ $e^{h\nu/kT} \gg 1$. For $\lambda = 5000 \text{ \AA}$ $e^{h\nu/kT} = 148$. Thus (47) can be replaced by (48).

$$\frac{n_2}{n_1} = \frac{g_2}{g_1} e^{-(h\nu_{12}/kT)} \quad (48)$$

Defining the vibrational temperature to be given by (49)

$$\frac{n_2}{n_1} = \frac{g_2}{g_1} e^{-(h\nu_{12}/kT_{VIB})} \quad (49)$$

it is seen $T_{VIB} = T = 5770^\circ$.

The assumption that stimulated emission can be ignored needs to be justified. For $e^{h\nu/kT} \gg 1$ it is possible to write (50).

$$B_{ji}\rho_{ij} = B_{ji}\sigma_{ij} e^{-(h\nu_{ji}/kT)} \quad (50)$$

Relations between the A and B coefficients, (44) and (51),

$$A_{ji} = B_{ij} \frac{g_i}{g_j} \sigma_{ij} \quad (44)$$

$$B_{ij} = \frac{g_j}{g_i} B_{ji} \quad (51)$$

are combined to give (52).

$$A_{ji} = B_{ji} \sigma_{ij} \quad (52)$$

Combining (50) and (52) results in (53).

$$B_{ji} \rho_{ij} = A_{ji} e^{-(h\nu_{ji}/kT)} \quad (53)$$

Equation (50) says the stimulated transition rate between level j and level i is much smaller than the spontaneous transition rate between level j and i.

The next step in theoretical band sequence flux ratio calculations is to write an expression for the band sequence fluxes. Again, consider a model consisting of two electronic states and the associated vibrational levels producing the Swan band sequences. An expression for the Δv band sequence flux can be written as (54)

$$F'_{B,s} \sim \sum_{V''} \sum_{\Delta v} [(n_{V''} B_{V''V'} \rho_{V''V'}) p_{V',V''} h\nu_{V',V''}] \quad (54)$$

In (54) V'' is a vibrational level in the lower electronic state from which absorption occurs, v' is a vibrational level in the upper

electronic state resulting from absorption, and v'' is a vibrational level in the lower electronic state resulting from a spontaneous emission from a level in the upper electronic state. The term $p_{v',v''}$ is the probability v' will deexcite to level v'' . It is given by (55).

$$p_{v',v''} = \frac{A_{v',v''}}{\sum_{v''} A_{v',v''}} \quad (55)$$

The sum $\sum_{v'-v''}$ is over the transitions producing the desired Δv and the sum $\sum_{v''}$ is over all the vibrational levels included in the lower electronic state. The band sequence flux ratios for C_2 are obtained by taking a ratio of (55) for two different Δv 's, say $\Delta v=+1$ and $\Delta v=0$.

Krishna Swamy and O'Dell (1986) have constructed the most elaborate C_2 statistical equilibrium model. Figure 1 shows the ten singlet and triplet electronic levels used in the model. Each electronic state has 14 vibrational levels. The triplet state c has not been observed in the laboratory or in cometary comae; but it has been inferred from perturbations of the A state (Ballik and Ramsay 1963). In addition triplet-singlet transitions, designated as a-X, b-X, and c-X in figure 1, were included in the model. These transitions are forbidden and have not been observed in cometary comae or in the laboratory.

The A and B coefficients for an electronic transition depend on the electronic transition moment, $|R_e|^2$. The transition moment is related to the oscillator strength. Krishna Swamy and O'Dell have used the most recent laboratory and theoretically determined values for the transition moments. However, the intercombination transition moments are entirely unknown and have been left as variable parameters in the calculations.

The equations of statistical equilibrium were written and solved for the level populations. The band sequence flux ratios were calculated for $F(C_2 \Delta v=+1)/F(C_2 \Delta v=0)$ and $F(C_2 \Delta v=-1)/F(C_2 \Delta v=0)$. Table 12 shows the model determined Swan band sequence flux ratios for various a-X electronic transition moments, suppressing the b-X, c-X, d-c, and c-X transitions. The upper row for each band sequence flux ratio is for a heliocentric distance of 0.5 AU while the lower row is for a heliocentric distance of 1.5 AU. At the top of columns 3-6 the a-X electronic transition moment used to calculate ratios below them are given.

TABLE 12

Effect of a-X Transition on Swan Band Sequence Flux Ratios					
	AU	10^{-7}	10^{-6}	10^{-5}	10^{-4}
$\log \left(\frac{F(C_2 \Delta v=+1)}{F(C_2 \Delta v=0)} \right)$	0.5	-0.143	-0.149	-0.202	-0.410
	1.5	-0.155	-0.200	-0.397	-0.714
$\log \left(\frac{F(C_2 \Delta v=-1)}{F(C_2 \Delta v=0)} \right)$	0.5	-0.302	-0.304	-0.323	-0.398
	1.5	-0.305	-0.321	-0.394	-0.490

Table 13 shows the results for calculations with $|R_e|^2_{(a-X)} = 10^{-5}$, $|R_e|^2_{(c-X)} = 10^{-3}$, and $|R_e|^2_{(c-d)} = 0$. At the top of columns 3-6 the b-X electronic transition moments used to calculate the ratios below them are given.

TABLE 13

Effect of b-X Transitions on Swan Band Sequence Flux Ratios					
	AU	10^{-5}	10^{-4}	10^{-3}	10^{-2}
$\log \left(\frac{F(C_2 \Delta v=+1)}{F(C_2 \Delta v=0)} \right)$	0.5	-0.203	-0.207	-0.213	-0.213
	1.5	-0.398	-0.400	-0.404	-0.398
$\log \left(\frac{F(C_2 \Delta v=-1)}{F(C_2 \Delta v=0)} \right)$	0.5	-0.323	-0.325	-0.327	-0.328
	1.5	-0.394	-0.395	-0.396	-0.395

From tables 12 and 13 it is seen the a-X transition has the greatest effect on the Swan band sequence flux ratios. The b-X transition has little effect on the ratios. Krishna Swamy and O'Dell also find the c-d and c-X transition have little effect on the Swan band sequence flux ratios.

VII. Previous Observational Determinations of
Swan Band Sequence Flux Ratios

This section describes previous observational determinations of the $F(C_2 \Delta v=+1)/F(C_2 \Delta v=0)$ and the $F(C_2 \Delta v=-1)/F(C_2 \Delta v=0)$ Swan band sequence flux ratios. The objective of this section is to put the Halley measurements made by the author into context with previous measurements.

Mayer and O'Dell (1968) observed Comet Rudnicki from the University of Chicago's Yerkes Observatory. They used a rotating grating spectrophotometer over the wavelength interval from 3500 Å - 5500 Å with 35 Å step sizes and an 8 sec per channel integration time. Table 14 shows their results for the $F(\Delta v=+1)/F(\Delta v=0)$ Swan band sequence flux ratio.

TABLE 14

Mayer and O'Dell's Swan Band Sequence Flux Ratios

	Date U.T. 1966	r (AU)	$\frac{F(\Delta v=+1)}{F(\Delta v=0)}$
Dec.	3.08	1.188	0.459
	4.04	1.170	0.460
	12.03	1.028	0.441
	13.03	1.009	0.476
	14.02	0.991	0.469
	15.02	0.972	0.475

Gebel (1970) determined Swan band sequence flux ratios for Comets 1967n, 1968b, and 1968c at the University of Chicago's Yerkes Observatory. Gebel used a photoelectric spectrophotometer with a rotating grating to cover a wavelength interval between 3500 Å and 6300 Å. He used 35 Å step sizes and an 8 sec per channel integration time. Table 15 gives his results.

TABLE 15

Gebel's Swan Band Sequence Flux Ratios

Object/Date (1968)	r	$\frac{F(\Delta v)}{F(\Delta v=0)}$	
		$\Delta v=+1$	$\Delta v=-1$
1967n			
Feb 5	1.717	0.520	0.367
Mar 6	1.703	0.588	0.483
Mar 27	1.746	0.569	0.511
Mar 28	1.749	0.598	0.477
Mar 29	1.753	0.550	0.421
Apr 5	1.778	0.516	0.575
1968b			
Jun 19	1.257	0.477	0.273
1968c			
Jul 25	1.178	0.562	0.416
Jul 31	1.166	0.545	0.480
Aug 1	1.164	0.566	0.522
Sep 12	1.293	0.541	0.502
Sep 24	1.384	0.524	0.382
Sep 26	1.400	0.635	0.492
Sep 27	1.408	0.499	0.619

O'Dell (1971) observed Comet 1969g with the 41-in refractor and a grating spectrograph at the Yerkes Observatory. He obtained $F(\Delta v=+1)/F(\Delta v=0) = 0.6 \pm 0.1$.

A'Hearn (1975) observed Comet Kohoutek at the Lowell Observatory with a Fourier Spectrometer mounted on the 31-in. and 24-in. telescopes. The wavelength interval from 3800 Å to 8400 Å was covered. A bandpass of 10-15 Å was used. Table 16 gives A'Hearn's results.

TABLE 16
A'Hearn's Swan Band Sequence Flux Ratios
(Comet Kohoutek)

Date (U.T.)	r (AU)	$\frac{F(\Delta v)}{F(\Delta v=0)}$	
		v=+1	v=-1
Dec 4.55	0.794	0.542	0.500
Dec 5.55	0.744	0.524	0.490
Dec 6.55	0.719	0.529	0.519
Dec 7.55	0.667	0.532	0.534
Jan 12.09	0.552	0.538	0.494
Jan 28.13	0.957	0.500	0.503
Jan 29.13	0.979	0.532	0.512
Jan 30.17	1.003	0.480	0.484
Jan 31.16	1.025	0.526	0.527
Feb 1.12	1.046	0.409	0.415
Feb 2.16	1.069	0.698	0.431

Table 17 shows Swan band sequence flux ratios determined by Chaubey (1978) from Comet West at the Uttar Pradesh State Observatory, India. A

52 cm telescope and photoelectric spectrophotometer covered the wavelength interval from 3500 - 6500 Å. The exit slot was 35 Å wide.

TABLE 17
Chaubey's Determination of Swan Band Sequence Ratios
(Comet West)

Date March, 1976 (U.T.)	r (AU)	F(Δv)/F($\Delta v=0$)	
		$\Delta v=+1$	$\Delta v=-1$
6.01	0.400	0.586	0.383
6.99	0.427	0.600	0.433
8.01	0.455	0.645	0.527
11.01	0.535	0.635	0.590
12.98	0.587	0.669	0.580
13.99	0.613	0.531	0.585
16.99	0.689	0.673	0.590
17.98	0.713	0.680	0.598
20.99	0.786	0.684	0.602
23.96	0.833	0.701	0.607

Sivaraman (1979) observed Comet West from the Kavalur Observatory, India. A 102-cm. reflector and photoelectric spectrophotometer scanned the wavelength interval from 3700 Å - 5700 Å. Exit slot widths ranged from 10 Å - 50 Å in the first and second orders. Table 18 shows Sivaraman's results.

TABLE 18

Sivaraman's Determination of Swan Band Sequence Flux Ratios
(Comet West)

Date March, 1976 (U.T.)	r (AU)	F(Δv)/F($\Delta v=0$)	
		$\Delta v=+1$	$\Delta v=-1$
12.98	0.588	0.696	
13.98	0.611	0.641	0.570
14.98	0.633	0.688	0.613
16.97	0.684	0.566	0.510
19.96	0.756	0.751	
20.96	0.782	0.610	
21.97	0.809	0.589	
23.97	0.853	0.603	

A'Hearn (1980) also made observations of Comet West. The 0.9-m telescope at the Goddard Space Flight Center was used with a Fourier Transform Spectrophotometer. The wavelength interval from 3700 Å - 8200 Å was covered with 3.3 Å - 19.4 Å bandpasses. Table 19 gives the results.

TABLE 19

A'Hearn's Determination of Swan Band Sequence Flux Ratios
(Comet West)

Date (1976)	r (AU)	F(Δv)/F($\Delta v=0$)	
		$\Delta v=+1$	$\Delta v=-1$
Mar 22-23	0.84	0.467	0.517
Mar 23-24	0.86	0.477	0.527
Mar 25-26	0.91	0.498	0.529
Mar 27-28	0.96	0.507	0.465
Mar 28-29	0.98	0.542	0.486

Goyara (1984) observed Comet Austin with 104cm reflector at the Uttar Pradesh State Observatory, India. A photoelectric spectrophotometer was used over the wavelength interval from 3300-7500Å. An exit slot with 50 Å bandpass in the first order was used. Table 20 gives Goyara's results.

TABLE 20

Goyara's Determination of Swan Band Sequence Flux Ratios
(Comet Austin)

Date Sep, 1982 (U.T.)	r (AU)	F(Δv)/F($\Delta v=0$)	
		$\Delta v=+1$	$\Delta v=-1$
5.6	0.70	0.533	0.555
8.6	0.73	0.521	0.438
9.6	0.74	0.564	0.444
18.6	0.83	0.459	0.439
20.6	0.86	0.440	0.478
21.6	0.87	0.472	0.545

VIII. Summary and Conclusions

In this, the last section, a summary of the observational results determined by the author is made. Special attention is given to the usefulness of accurate determinations of the OH band fluxes and the C_2 band sequence fluxes.

From table 10 it is seen the accuracy of the OH band is given as 3.7%. Accurate observations of the OH band are valuable as a means of linking the optical observations described and analyzed here to ultraviolet Halley observations made by the International Ultraviolet Explorer. In particular the Mulliken bands in the ultraviolet are of interest. Determination of the $\Delta v = 0$ Mulliken band sequence flux relative to the $\Delta v = 0$ Swan band sequence flux provides a means of determining the singlet to triplet population ratio for cometary C_2 . Likewise the CN band at 9180 Å could be used to link the optical observations with infrared observations. However, the accuracy is not as good for the CN band, 7.3%. The accuracy is not as good as a result of the smaller signal (S-1 tube) and hence the larger photon noise.

The Swan band sequence fluxes have accuracies between 1-2%. The Swan band sequence flux ratios $F(\Delta v=+1)/F(\Delta v=0)$ and $F(\Delta v=-1)/F(\Delta v=0)$ are therefore well determined. With these band sequence flux ratios well determined, a comparison can be made to Krishna Swamy and O'Dell's model values of $F(\Delta v=+1)/F(\Delta v=0)$ and $F(\Delta v=-1)/F(\Delta v=0)$. It was seen in the discussion of Krishna Swamy and O'Dell's model that $F(\Delta v=+1)/F(\Delta v=0)$ is affected primarily by the value of the a-X transition moment. Hence, the observations can fix a value for the a-X transition moment. Figure

35 shows a plot of $F(\Delta v=+1)/F(\Delta v=0)$ vs heliocentric distance as determined from Krishna Swamy and O'Dell's model for various values of the a-X transition moment. The quantity $F(\Delta v=+1)/F(\Delta v=0)$ is a measure of T_{VIB} for the lowest triplet electronic state. Figure 35 shows the author's determination of $F(\Delta v=+1)/F(\Delta v=0)$ along with probable errors. Also, figure 35 shows other observational determinations of $F(\Delta v=+1)/F(\Delta v=0)$ made during the past two decades.

Without probable errors associated with the band sequence flux ratios made by other authors it is difficult to draw conclusions from a comparison between the observational results and the model predictions. However, the Gebel band sequence flux ratio, labelled B, C and N in figure 35, imply $F(\Delta v=+1)/F(\Delta v=0)$ has no dependence on heliocentric distance. The Gebel ratios then do not verify a model having a-X transitions as a T_{VIB} lowering mechanism for the lowest triplet state.

Figure 36 compares the observational and model determinations of $F(\Delta v=-1)/F(\Delta v=0)$ at various heliocentric distances in the same way as figure 35. Comparing the authors determination of $F(\Delta v=+1)/F(\Delta v=0)$ and $F(\Delta v=-1)/F(\Delta v=0)$ to model predictions in figure 35 and figure 36 imply $|R_e|^2 = 10^{-5}$ and $|R_e|^2 = 10^{-7}$. Hence, highly accurate measurements do not provide a unique value for the a-X electronic transition moment.

The Gebel observations and the observations made here force a reexamination of the C_2 model. The number of electronic and vibrational states used in the model argue for an adequate representation of the states and transitions involved. The solar radiation density is well known so perhaps a reexamination of the molecular constants used to determine the many Einstein A and B coefficients in the model is

required. Alternatively, a reexamination of the assumption of statistical equilibrium may be needed.

In regards to future observational work, high accuracy observations of Swan band sequence fluxes at large heliocentric distances are needed to verify Gebel's observations.

Figure 1. C_2 Electronic Energy Level Diagram.

Figure 2. The $\Delta V=0$ Swan Band Sequence.

Figure 3. Two-Channel Scanner : Optical Diagram.

Configuration No.	Wavelength	Filter	Tube
1	3000-4200	CuSO ₄ UG-5	S-20
2	4400-5800	GG-420	S-20
3	5300-7000	GG-495	S-20
4	5000-7000	GG-495	S-1
5	6500-10000	RG-610	S-1

Figure 4. Configurations

Figure 5. PMT Quantum Efficiencies.

Figure 6. Zenith Angle and Airmass Relation.
 $\sec(Z) = H/A = \text{airmasses}$

Figure 7. SEC(Z) vs Local Time for Halley Run Objects

Figure 8. Data Reduction Process

Figure 9. Extinction Coefficients ($\lambda = 5000\text{\AA}$ in Configuration 2).

Figure 10. Determination of the Rayleigh Component of Extinction.

Figure 11. Extinction Coefficients. This Work Filled Triangles,
Stone and Baldwin Filled Circles.

Figure 12. Extinction Coefficient Curve Fit to Stone and Baldwin Data.

Figure 13. Bregar Standard Star Fluxes Used for Extrapolation

```

/*program computes comet halley flux */
/*input files needed - skysub.cts, sensitivity, OH ext coeff*/
/*output - flux ergs cm-2sec-1A-1 3040-4160A*/

#include <stdio.h>
#include <math.h>
int j;
double logn,logN,k,n,secz,E,f,flam,logs,x,y,log10(),pow(),logE;
FILE *ifp, *ifpl, *ofp, *fp, *fopen();
main(argc,argv)
char *argv[];
int argc;
{
    x = 10;
    ifp = fopen(argv[1], 'r');
    fp = fopen(argv[2], 'r');
    ofp = fopen(argv[3], 'w');
    ifpl = fopen(argv[4], 'r');

    fscanf(ifp, '%f', &secz);

    for(j = 3040; j<=4160; j = j+20)
    {
        fscanf(ifp, '%f', &n);
        fscanf(fp, '%f', &logs);
        printf('\n%f', logs);
        logn = log10((double)n);
        if (j <= 3200)
            fscanf(ifpl, '%f', &k);
        else
            k = 0.06 + 1.175e14/pow((double)j,4.0);
        logN = logn + 0.4*k*secz;
        logE = logN - logs;
        y = logE;
        E = pow(x,y);
        f = E*j/1.509e26;
        flam = f*2.998e16/pow((double)j,2.0);
        fprintf(ofp, '\n%d%12.4e', j, flam);
    }
    fprintf(ofp, '\n');
}

```

Figure 21. C Program

Figure 35.

Figure 38.

Symbols for Figures 35 and 36

R: Comet Rudnicki, 1966e (Mayer, O'Dell 1968)
N: Comet 1967n (Gebel 1970)
B: Comet 1968b (Gebel 1970)
C: Comet 1968c (Gebel 1970)
K: Comet Kohoutek, 1973XII (A'Hearn 1975)
Circled K: Comet Kohoutek, 1973XII (Danylewych et al., 1978)
IX: Comet Kobayashi-Berger-Melon, 1975IX (Danylewych et al., 1978)
W: Comet West, 1976VI (A'Hearn et al., 1980)
Circle W: Comet West, 1976IV (Sivaraman et al., 1979)
Squared W: Comet West, 1976VI (Chaubey 1978)
A: Comet Austin, 1982g (Goraya et al., 1984)
Circled dot: Comet Halley, (Tegler, O'Dell 1986)

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