A HGH-RESOLUTION CATALOG OF COMETARY EMISSION LINES

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ABSTRACT

Using high-resolution spectra obtained with the Hamilton echelle spectrograph at Lick Observatory, we have constructed a catalog of emission lines observed in comets Swift-Tuttle and Brorsen-Metcalf. The spectra cover the range between 3800 Å and 9900 Å with a spectral resolution of $\lambda/\Delta\lambda \sim 42000$. In the spectra, we catalog 2997 emission lines of which we identify 2438. We find cometary lines due to H, O, C_2, CN, NH_2, C_3, H_2O^+, CH, and CH^+. We list 559 unidentified lines compiled from the two spectra and comment on possibilities for their origins. © *1996 American Astronomical Society.*

1. INTRODUCTION

Comets are thought to be the least modified remnant from the creation of the solar system, and an understanding of their composition can provide insight into the conditions in the early solar system and into the region of cometary formation (Spinrad 1987). Spectroscopy of the comae provides the only means of determining cometary composition from the Earth, and a substantial effort in recent years has focused on the observation and identification of new molecular species in comets. While most of the current effort concentrates on the infrared and longer wavelengths, the visible region of the spectrum remains incompletely explored.

Low resolution visible spectra are now routinely obtained for many comets (Newburn & Spinrad 1989; Cochran *et al.* 1992; Hicks & Fink 1996), showing the well-known bands of CN, C_3, C_2, and NH_2. At higher resolution ($\lambda/\delta\lambda \sim 40\,000-100\,000$), studies have had to concentrate on small regions of the visible spectrum: resolving individual bands to measure the band structure (Tegler & Wyckoff 1989; O'Dell *et al.* 1988), separating isotopic components (Kleine *et al.* 1995), and measuring the kinematics of hydrogen (Brown & Spinrad 1993; Magee-Sauer *et al.* 1990) and ionized water (Brown 1993; Scherb *et al.* 1990). Such spectra of small targeted regions of the visible spectrum are unlikely to detect previously unknown emissions.

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With the advent of echelle spectrographs, we can now simultaneously record a spectrum at high resolution with continuous coverage in the visible region. In this paper, we report results of echelle spectroscopy of of two bright comets and discuss our findings of identified and unidentified lines.

2. OBSERVATION AND DATA REDUCTION

The two comets were observed at Lick Observatory using the Hamilton echelle spectrograph (Vogt 1989). Comet Brorsen-Metcalf (23P/1989 N1) was observed on 1989 August 22 using the 3-m Shane telescope, while Comet Swift-Tuttle (109P/1992 S2) was observed on 1992 November 18 using the 0.6-m coudé auxiliary telescope. The observational circumstances are summarized in Table 1.

The exposures were obtained by centering the image of the comet on the slit and hand-guiding on the cometary motion. The Swift-Tuttle spectrum was recorded on a 2400^2 Ford CCD which is large enough to simultaneously record all 92 spectral orders, providing uninterrupted wavelength coverage from 3800 Å to 8700 Å, and partial coverage to 9900 Å. Binning of the CCD in the spectral dimension caused a slight undersampling of the resolution of the spectrograph. The Brorsen-Metcalf spectrum was recorded on a smaller 800^2 TI CCD, which recorded 41 partial spectral orders, giving partial wavelength coverage from 4000 to 5500 Å.

For each spectrum, flat-fielding of the multi-order two-

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TABLE 1. Observational circumstances.

	Swift-Tuttle	Brorsen-Metcalf
date and time (UT)	2:02 1992 Nov 18	11:28 1989 Aug 22
exposure length (sec)	3000 sec	1800
geocentric dist. (AU)	1.213	0.726
geocentric vel. (km s^{-1})	+15	+46
heliocentric dist. (AU)	1.045	0.688
heliocentric vel. (km s^{-1})	−12	−53
aperture size (arcsec)	1.3×2.5	6.5×12.5
projected ap. size (km)	1140×2190	3400×6600
spectral range	3800–9900 Å	4000–5500 Å

dimensional spectrum was accomplished by dividing by a long-slit quartz lamp spectrum taken the same night. The exact order locations of each spectrum were determined by a deckered quartz lamp spectrum, also taken the same night. A 3-pixel-wide swath around each of these order locations was then extracted to produce a one-dimensional spectrum of each order. The echelle blaze function was removed by dividing each order by the average one-dimensional order profile of the quartz spectrum. The wavelength scale was determined from a fit to the spectrum of a thorium-argon lamp with a high density of known emission lines. Sample sections of the reduced one-dimensional spectra of comets Swift-Tuttle and Brorsen-Metcalf are shown in Fig. 1.

For each comet, every significant peak in the one-dimensional spectrum was checked against the two-dimensional echelle image to distinguish between real lines and apparent lines due to radiation events and CCD defects. In this manner, we found 2997 emission lines in the comets. We determined the wavelength of each emission line with a second order polynomial fit to the line core, which gave a typical accuracy of $\pm\sim 0.05$ Å. Emission lines from the sky, primarily due to OH, were identified and removed using the tabulation of Osterbrock *et al.* (1996).

3. LINE IDENTIFICATION

Many of the 2997 emission lines fall in well known molecular bands. We compared the line positions and intensities to positions and intensities from laboratory spectra of all species known to have cometary emissions in the visible wavelength region [based on the compilations of Arpigny (1994) and Festou *et al.* (1993)]. In attempting to identify the lines, both wavelength and relative intensity have been taken into account; molecular lines have been identified only if several transitions in a particular band are present, at the correct wavelength and relative intensity. A total of 2438 lines were identified with known cometary emitters in this manner.

An attempt was made to identify the remaining 559 lines. We compiled a list of laboratory wavelengths of many molecules with visible emissions which could plausibly be contributors. Table 2 lists all of the molecules for whose emissions we searched and the references to the laboratory spectra. No new species were identified.

Table 3 list all of the lines found in comets Swift-Tuttle and Brorsen-Metcalfe and their identifications, if known. This table, along with separate tables for each identified molecule and for the unidentified lines, can be accessed in electronic form at `http://ptolemy.gps.caltech.edu/~mbrown/comet/echelle.html` via an internet browser. In the table, column (1) lists the wavelength at which the line was measured in the spectrum of comet Swift-Tuttle. A "+" in this column indicates that the line with the wavelength listed in the previous row has been identified as a blend of two or more lines, with the laboratory wavelengths and identifications given in the subsequent rows. Column (2) gives the relative intensity of the emission line, with the brightest detected line equal to 1000. These intensi-

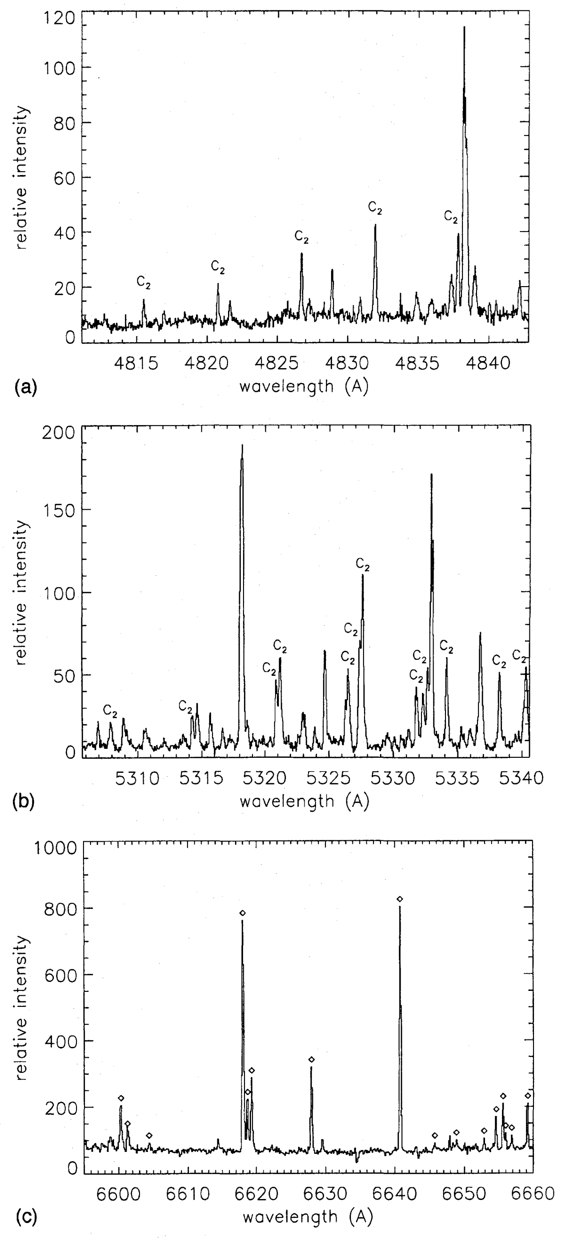

FIG. 1. Sample regions of high resolution comet spectra. (a) A region showing the unidentified lines near 4838 Å and a small part of the C_2 (0,0) band. (b) A region showing the strong unidentified lines near 5320 Å and part of the C_2 (0,1) band. (c) A region of strong NH_2 lines. All lines marked with a diamond are members of the NH_2 (0,7,0) band.

TABLE 2. Laboratory spectra references.

Molecule	Reference	Molecule	Reference
C_2	Phillips & Davis (1968)	H_3	Dabrowski and Herzberg (1980)
C_3	Merer (1967)		Herzberg & Watson (1980)
	Kiess and Bass (1954)		Herzberg *et al.* 1982
	Douglas (1951)	HNO	Dixon and Rosser (1985)
	Clusius and Douglas (1954)	HSO	Kakimoto *et al.* 1980
CN	Davis and Phillips (1968)	HCNO	Noble *et al.* (1984)
	Jevons (1926)	H_2CS	Judge & King (1979)
CH	Gerö (1941)	H_2CCS	Cloutheir (1987)
	Kiess & Broida (1956)	NH	Lunt *et al.* (1935)
	Moore & Broida (1959)		Judge & Moule (1980)
CH^+	Douglas & Herzberg (1942)		Suzuki *et al.* (1983)
NH_2	Dressler & Ramsay (1959)	OH	Dejardin *et al.* (1953)
	Ross *et al.* 1988		Dieke & Crosswhite (1962)
	Dixon *et al.* (1991)		
	Arpigny (1995)	S_2	Naudé (1945)
H_2O^+	Lew (1976)	SiN	Bredohl *et al.* (1976)
CO	Coster & Brons (1934)	SiO	Verma & Mulliken (1961)
	von Schmid and Gerö (1935)	SiH_2	Dubois (1968)
	Johnson & Asundi (1929)	CO^+	Coster *et al.* (1932)
CCO	Devillers & Ramsay (1971)		Rao (1950)
CCN	Kakimoto & Kasuya (1982)	$CS_2{}^+$	Balfour (1976)
CH_2	Petek *et al.* (1987)	H_2S^+	Duxbury *et al.* (1972)
CNO	Ramsay & Winnewisser (1983)	H_2CCOH^-	Mead *et al.* (1984)
C_2H_3O	Inoue & Akimoto (1981)	$N_2{}^+$	Douglas (1953)
HCO	Herzberg & Ramsay (1955)	N_2O^+	Aarts & Callomon (1987)
		OH^+	Weniger & Herman (1958)

TABLE 3. Sample of the catalog of emission lines.*

λ, ST	*I*, ST	λ, BM	*I*, BM	λ, lab	Species	Band	Transition
		4361.71	13	4361.77	C_2	(3,1)	$R_2(03)$
4364.51	25			4364.50	C_2	(4,2)	$P_1(29)+P_2(28)+P_3(27)$
+				4364.50	C_2	(4,2)	$P_1(28)+P_2(18)+P_3(16)$
4364.66	22			4364.70	C_2	(4,2)	$P_1(22)+P_1(26)+P_2(26)+P_3(18)$
4364.80	20			4364.78	C_2	(4,2)	$P_1(23)+P_2(24)+P_3(19)$
4364.99	21			4364.94	C_2	(4,2)	Bandhead
4371.26	16	4371.26	20	4371.44	C_2	(3,1)	Bandhead
		4381.08	12	4381.08	C_2	(2,0)	$P_1(14)+P_3(28)$
		4381.48	15	4381.41	C_2	(2,0)	$P_1(15)$
		+		4381.52	C_2	(2,0)	$P_1(27)+P_3(26)$
		+		4381.44	C_2	(2,0)	$P_1(16)+P_2(27)$
		+		4381.41	C_2	(2,0)	$P_1(28)+P_3(13)$
4381.70	15			4381.72	C_2	(2,0)	$P_1(26)$
4381.96	17	4381.90	24	4382.15	C_2	(2,0)	Bandhead
4428.45	9	4428.45	20		unid		
		4439.88	11		unid		
		4452.20	10		unid		
		4510.83	11	4510.84	NH_2	(0,15,0)	1_{01}-1_{11}
4510.99	17	4510.99	14	4511.00	NH_2	(0,15,0)	3_{03}-3_{13}
+		+		4511.14	NH_2	(0,15,0)	2_{02}-2_{12}
4515.57	17	4515.59	14	4515.59	C_2	(1,0)	$R_1(87)+R_2(86)+R_3(85)$
		4516.87	10		unid		
		4519.14	9		unid		
4519.59	16	4519.69	10	4519.69	C_2	(1,0)	$R_1(86)+R_2(85)+R_3(84)$
		4520.10	10		unid		
4521.45	20	4521.41	18	4521.41	NH_2	(0,15,0)	1_{01}-2_{11}
		4521.55	16		unid		
		4521.75	11		unid		
		4522.13	9		unid		
		4523.20	9	4523.15	C_2	(1,0)	$R_1(85)+R_2(84)+R_3(83)$
4523.74	19	4523.70	13	4523.42	C_2	(2,1)	$R_1(82)+R_2(81)+R_3(80)$
		4525.12	12		unid		
4526.90	16	4526.79	13	4526.80	C_2	(2,1)	$R_1(81)+R_2(80)+R_3(79)$
4527.28	16	4527.24	11	4527.20	C_2	(1,0)	$R_1(84)+R_2(83)+R_3(82)$
		4527.73	11		unid		
		4528.27	12	4528.25	NH_2	(0,15,0)	2_{02}-3_{12}
		4529.90	10		unid		
		4530.17	9		unid		
		4530.58	11	4530.63	C_2	(1,0)	$R_1(83)+R_2(82)+R_3(81)$
		+		4530.30	C_2	(2,1)	$R_1(80)+R_2(79)+R_3(78)$
		4531.15	11		unid		
4533.53	19	4533.56	10	4533.63	C_2	(2,1)	$R_1(79)+R_2(78)+R_3(77)$

Table 1 can be found in AAS CD-ROM, Vol. 7, 1996. Only the first page is shown here for form and content.

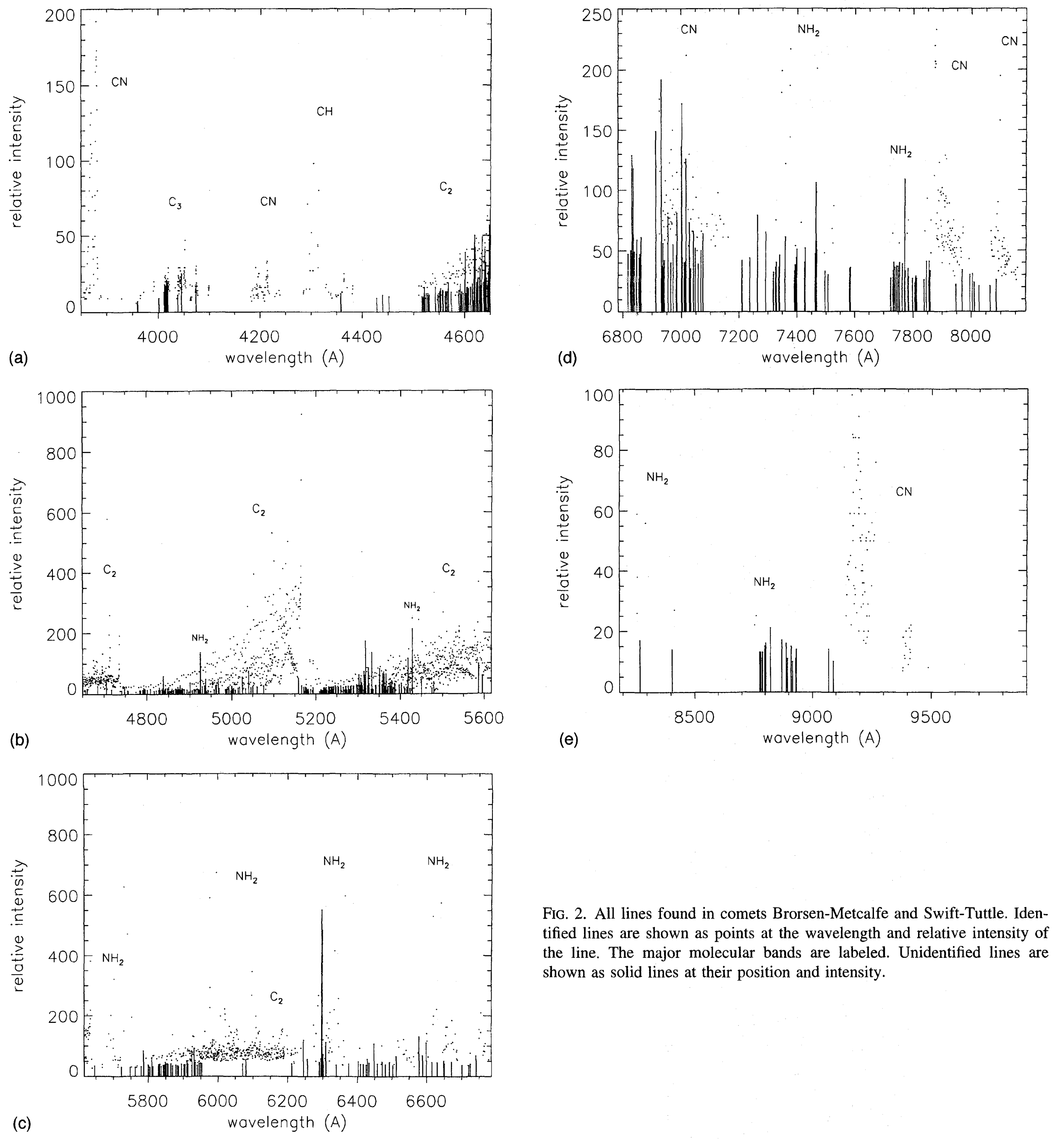

FIG. 2. All lines found in comets Brorsen-Metcalfe and Swift-Tuttle. Identified lines are shown as points at the wavelength and relative intensity of the line. The major molecular bands are labeled. Unidentified lines are shown as solid lines at their position and intensity.

ties are corrected for the echelle blaze function, but not for CCD response or atmospheric absorption. The relative intensities are thus reliable within a spectral order but not between widely spaced orders. Columns (3) and (4) are identical to columns (1) and (2), but for comet Brorsen-Metcalf. Column (5) lists the laboratory wavelength of the given identification. Columns (6), (7), and (8) give the identified molecule, band, and transition, respectively. If the emission line is unidentified, column (6) states ''unid.'' Figure 2 shows, in graphical form, the wavelength and relative intensity of all cometary lines. Identified lines are shown as points, unidentified lines are shown as complete lines, and the major identified molecular bands are indicated.

4. UNIDENTIFIED LINES

Shortward of the beginning of the C_2 Swan band at 5600 Å, most of the unidentified bands are grouped within the known molecular bands. We therefore suggest that many of these lines are unclassified lines belonging to the neighboring bands of C_2, NH_2, or C_3. In this region of the spectrum, we draw attention to the complex of lines around 4838 Å and around 5325 Å (see Fig. 1), which do not appear to follow this general trend, and to the three lines at 4428.45, 4439.88, and 4452.20 Å, which are not particularly bright but fall well outside any known band.

The brightest of the unidentified lines occur in the ~6000–7000 Å region, closely associated with identified NH_2 bands, and in low-resolution cometary spectra these lines are assumed to be a part of the neighboring NH_2 band (e.g., Wyckoff *et al.* 1988). We strongly suspect that these are indeed lines of NH_2 which have not been identified in the high-resolution laboratory spectra. In particular, most of the NH_2 laboratory work has been on absorption spectroscopy, so many of the high-lying transitions have not been observed. Recent work on laser-induced fluorescence spectroscopy of NH_2 should allow (Dixon *et al.* 1991) the laboratory identification of many higher angular momentum states.

Finally, several clumps of unidentified lines in the 7000–9000 Å region of the spectra do not appear to be associated with any known bands. Most prominent of these is an isolated cluster between 6818 and 6863 Å, which may continue to 7180 Å mixed with a CN band. Another isolated cluster around 9000 Å is also unidentified.

In the future, we plan to aid the identification of unknown cometary emission lines by their spatial distribution; spectra will be obtained at many different positions in the coma of the comet, and emissions from a common species will have a common spatial distribution. In this manner, the many emission lines that are suspected to be unclassified lines of known emitters will be identified, and lines from any truly unknown emitting species will become more apparent.

5. CONCLUSIONS

We have cataloged a total of 2997 emission lines between 3855 Å and 9567 Å in comets Brorsen-Metcalfe and Swift-Tuttle. Of these lines, 1595 contain contributions due to C_2, 371 due to CN, 303 due to NH_2, 130 due to C_3, and 5 due to atomic hydrogen or oxygen. The remaining 559 lines remain unidentified even after an intensive search for new molecular species. We suggest that the majority of the unidentified lines are previously unclassified lines due to the known molecule species.

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