Spectra of Comets: Infrared and Radio Regions.

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Abstract.

The spectroscopy of comets at radio and infrared wavelengths is reviewed, with an emphasis on recent results. An inventory of the needs for molecular data is made.

1. Introduction

The opening of cometary spectroscopy to the radio and infrared regions is very recent. These spectral regions, compared to the visible region, are especially important because they contain the signals of parent molecules directly sublimated from the nucleus. Therefore, they allow us to investigate the molecular composition of cometary volatiles, giving basic informations on the nature of comets and important clues to their formation mechanisms.

H_2O, CO_2 and CH_3OH are molecules firmly identified in cometary infrared spectra. Several other features, yet unidentified, are present and other molecules are suspected. The HCN, CO, H_2CO, CH_3OH and H_2S molecules are observed in comets through their rotational lines in the millimetre-submillimetre domain; some of them, like methanol, through many lines. In addition, the 18-cm lines of the OH radical have been observed in tens of comets.

Cometary atmospheres are similar to the supersonic molecular jets observed in the laboratory. The lines have Doppler shapes with a very small thermal dispersion. The high spectral resolution of microwave spectroscopy permits a detailed study of the kinematics of the cometary jets. For this, an accurate knowledge of the line frequencies and of the hyperfine structures is required.

A challenge to cometary spectroscopists is the interpretation of the 3.2-3.6 μm strong emission now observed in several comets. Methanol is definitely contributing, but excess emissions are present at 3.28 μm, attributed to aromatics, and around 3.4 μm, presumably due to CHO species. Emission features of unknown origins are also noted at 2.44, 2.8, and 6.8 μm. Their identification will require the observation of high-resolution spectra in bright comets.

Radio and infrared observations of cometary spectra are presently made with state-of-the-art techniques and still suffer from limited signal-to-noise ratios. New prospects will be offered in the future with the opening of extended ground-based facilities, the availability of Earth-orbit observatories such as ISO or FIRST, and of course the *in situ* exploration of a comet with the ROSETTA probe, which could be equipped with high-resolution infrared and radio spectrometers.

Table 1. Molecular radio lines detected in comets.

frequency MHz	species	transition	comet[a]	comments	references[b]
decimetric					
1612	OH	ground F1-2	M, L		Boc92
1665	OH	ground F1-1	K...	more than 40 comets	Bir74
1667	OH	ground F2-2	K...	"	Bir74
1721	OH	ground F2-1	M, L		Boc92
3335	CH	ground F1-1	K	not confirmed	Bla74
centimetric					
4830	H_2CO	1_{10}-1_{11}	P/H	marginal	Sny89
8188	?		K	marginal, unident.	Gig75
22235	H_2O	6_{16}-5_{23}	B, IAA	not confirmed	Jac76 Alt84
23870	NH_3	(3,3)-(3,3)	IAA	not confirmed	Alt84
millimetric					
89088	HCN	1-0	K, P/H...		Hue74 Des86
967xx	CH_3OH	(2,K)-(1,K) [s]	A, L		Boc91 Boc94a
110700	CH_3CN	6-5 $\nu_8 = 1$	K	not confirmed	Uli74
1451xx	CH_3OH	(3,K)-(2,K) [s]	A, L...		Boc91 Boc94a
165xxx	CH_3OH	(J,K)-(J,K-1) [s]	L, P/ST		Boc94a
168763	H_2S	1_{10}-1_{01}	A...		Boc91 Cro91
216710	H_2S	2_{20}-2_{11}	L		Cro91
218440	CH_3OH	(4,2)-(3,1)E	L		Boc94a
225698	H_2CO	3_{12}-2_{11}	P/BM...		Col92
230538	CO	2-1	P/SW1		Sen94
265886	HCN	3-2	P/BM, A...		Boc90
submillimetric					
338xxx	CH_3OH	(7,K)-(6,K) [s]	P/ST		Boc94b
341416	CH_3OH	(7,1)-(6,1)A-	P/ST		Boc94b
351767	H_2CO	5_{15}-4_{14}	L, P/ST		Sch92 Boc94b
354505	HCN	4-3	L, P/ST		Sch92 Boc94b
2509949	OH	5/2-3/2	P/H	KAO with Fabry-Perot	Sta87

[a]Full designation of comets: A: Austin 1990 V; B: Bradfield 1974 III; P/BM: P/Brorsen-Metcalf 1986 IX; P/H: P/Halley 1986 III; IAA: IRAS-Araki-Alcock 1983 VII; K: Kohoutek 1973 XII; L: Levy 1990 XX; M: Meier 1978 XXI; P/SW1: P/Schwassmann-Wachmann 1 1989 XV; P/ST: P/Swift-Tuttle 1990 XXVIII.

[b]Only references to first detections are given; Alt84: Altenhoff et al. 1984; Bir74: Biraud et al. 1974; Bla74: Black et al. 1974; Boc90: Bockelée-Morvan et al. 1990a; Boc91: Bockelée-Morvan et al. 1991; Boc92: Bockelée-Morvan et al. 1992; Boc94a: Bockelée-Morvan et al. 1994a; Boc94b: Bockelée-Morvan et al. 1994b; Col92: Colom et al. 1992; Cro91: Crovisier et al. 1991; Des86: Despois et al. 1986; Gig75: Giguere & Clark 1975; Hue74: Huebner et al. 1974; Jac76: Jackson et al. 1976; Sch92: Schloerb & Ge 1992; Sen94: Senay & Jewitt 1994; Sny89: Snyder et al. 1989; Sta87: Stacey et al. 1987; Uli74: Ulich & Conklin 1974.

[s]Several lines are observed near the same frequency; in this case, the last digits of the frequency are not given.

Other recent reviews on these topics were given by Crovisier (1992) and Crovisier & Schloerb (1991); see also the companion paper on visible and UV spectroscopy by Arpigny (*this workshop*).

An exceptional observing opportunity was offered in July 1994 when the fragments of the nucleus of comet P/Shoemaker-Levy 9 impacted Jupiter (IAU Circ. No 6017–6053). During the multi-wavelengths observing campaign of this event, radio spectroscopy resulted in the detection of the CO, CS and possibly OCS molecules at millimetre wavelengths, of the HCN molecule in the submillimetre region (whereas no microwave molecular lines were ever observed before in Jupiter). Some of these molecular signals persisted for several weeks. Infrared observations showed enhancements of many molecular features (CH_4, CO, H_3^+) with respect to the "quiet" Jupiter spectrum, and the transient emission of H_2O lines (ν_2 band) just after the impacts. The analyses of these observations are just beginning. It is hard to tell at the present time whether the observed molecular species are coming from cometary material, from chemical processing during and after the blast of cometary and Jupiter material, or from unchanged material coming from the deep atmosphere of Jupiter. If these processes can be understood and modelled, it might be possible to retrieve information of the original chemical composition of the comet.

2. The Radio Spectrum

2.1. Observations

The most important steps in the radio spectroscopic observations of comets were the detection of the OH 18-cm lines in comet Kohoutek in 1973, the confirmed detection of HCN at millimetric wavelengths in P/Halley in 1985, the detections of the H_2S and CH_3OH molecules in comets Austin and Levy and the opening to the submillimetric domain in 1990, and recently the detection of the CO J(2-1) line in the distant comet P/Schwassmann-Wachmann 1.

Table 1 lists all radio lines whose detection in comets was reported. For historical purposes, several unconfirmed detections are also listed. This list is very modest, compared to the more than 5000 radio lines of nearly a hundred molecular species detected in the interstellar medium (Lovas 1992). Cometary lines are weak compared to interstellar lines even in the brightest comets observed so far. Long integration times are needed whereas bright comets are rare and appear during short observational windows. On the other hand, the pressure on the schedule of the large instruments which are needed for such observations is very heavy, and target-of-opportunity observations of unexpected comets are not easy to schedule. The observations have to be restricted to narrow spectral domains where "interesting" lines were expected to be present. Therefore, only a few percent of the microwave spectrum of comets has been explored with a significant sensitivity up to now.

2.2. Cometary Composition

Radio spectroscopy, due to its large resolution and the high accuracy with which line frequencies are known, allows one to make unambiguous identifications. Most of the parent molecules now known to be present in comets were first firmly identified by radio spectroscopy (Crovisier 1994 and Arpigny *this workshop*). Minor species such as H_2S and HCN were detected with abundances of the order of 0.1 % only, and stringent upper limits were put on several species (Crovisier et al. 1993). However, since only a small fraction of the microwave spectrum has been explored, we may expect that several species have still escaped detection.

2.3. Line Shapes

A unique advantage of radio techniques is their high spectral resolution which allows one to resolve the lines. In the low density cometary atmospheres, spectral lines have Doppler shapes.

The line widths are related to the expansion velocity of the cometary atmosphere. For parent species, the FWHM is roughly twice the expansion velocity (which is typically 0.8–1.2 km s^{-1}). For secondary species such as OH, one has to take into account the ejection velocities given to the fragments during the photolytic process, and modelling is required to retrieve the expansion velocity (Bockelée-Morvan et al. 1990b). Line widths measurements (especially from the large OH data base) show that, as expected from hydrodynamical models, the expansion velocity increases when the comet is approaching the Sun, and when the gas production rate is higher.

The asymmetries of the lines are related to the anisotropic outgassing of the cometary nuclei. An example is shown in Fig. 1. This phenomenon is responsible for a reaction effect on the comet nucleus which perturbs its orbit. The modelling of such non-gravitational effects and its comparison with the accurate astrometric measurement of cometary orbits is, at the present time, the only way for us to have access to the masses of the cometary nuclei, and, indirectly, to their density. The cometary lines are currently displaced by 0.1–0.2 km s^{-1} by this phenomenon. In the best cases (cf. Fig. 1), these offsets can be accurately measured. However, the microwave line frequencies of some molecules are not all so reliably known. For instance, the methanol lines aroung 145 GHz, which were extensively observed in recent comets, are only known within ± 50 kHz, which corresponds to ± 0.1 km s^{-1}.

Some kind of a record was set with the observation of the CO line in comet P/Schwassmann-Wachmann 1 (Senay & Jewitt 1994; Lellouch et al. 1994). The line is very narrow (Fig. 1): its FWHM is only 0.14 km s^{-1}. This is one of the narrowest lines ever observed in astrophysics. It corresponds to a kinetic temperature of 10–15 K. P/Schwassmann-Wachmann 1 is an atypical comet which has a nearly circular orbit at 6 AU from the Sun and which undergoes strong and unpredictible outbursts as well as a sustained quiescent activity. At this distance, the temperature is two low to allow significant water sublimation, and the cometary activity must be driven by more volatile species. The recent detection of CO informs us on the nature of these species (other candidates could be N_2 or CO_2). The blueshift of the line (about 0.5 km s^{-1}; Fig. 1) shows that the gas sublimation is occuring preferentially towards us (i.e. towards the Sun), and the very narrow width shows that the cometary atmosphere is cooling very efficiently when it expands.

The OH 18-cm lines are very sensitive to the *Fievez-Zeeman*[1] effect, i.e. the frequency shift between the left- and right-hand circular polarization components due to the magnetic field. This effect was searched for with the Nançay radio

Figure 1. Top: the H_2CO line at 227 GHz observed in comet P/Swift-Tuttle 1992 XXVIII with the IRAM 30-m telescope (from Despois et al. 1994). Bottom: the CO $J(2-1)$ line at 230 GHz observed in comet P/Schwassmann-Wachmann 1 with the IRAM telescope (Lellouch et al. 1994 and *in preparation*); the narrow component is 0.14 km s^{-1} wide and blueshifted by 0.5 km s^{-1} with respect to the comet nucleus.

Figure 2. Average 1667–1665 MHz OH spectrum of comet Levy 1990 XX observed on Aug. 31 to Sep. 3 1990 at Nançay in right-handed (thick line) and left-handed (dotted line) circular polarizations. The Zeeman frequency shift corresponds to a line-of-sight magnetic field of 23 ± 3 nT towards the observer (from Bockelée-Morvan et al. 1992).

telescope in comets for which the OH lines were peculiarly intense. It was tentatively detected in comet Austin 1982 VI for which a projected magnetic field $< B_p >= 50 \pm 21$ nT was estimated (Gérard 1985). It was clearly detected in comet Levy 1990 XX at the end of August 1990 (Fig. 2), with $< B_p >= -23 \pm 3$ nT (Bockelée-Morvan et al. 1992). This magnetic field results from the piling up of the interplanetary medium magnetic field in the vicinity of the comet. The intensities derived in comets Austin and Levy from the OH lines agree well with the typical values measured *in situ* in comet Halley by the space probes.

2.4. Unidentified Features

Several unidentified features were indeed listed by Crovisier et al. (1993) and another one is indicated in Table 1, but they were only observed at a marginal level.

3. The Infrared Spectrum

3.1. Observations

Table 2 lists the molecular bands and the unidentified features observed in comets. The near-infrared is dominated by emissions by radicals: the Meinel bands of OH, the red system of CN ($A^2\Pi_i$–$X^2\Sigma^+$) and the Phillips ($A^1\Pi_u$–

[1] We learned at this workshop, dedicated to the memory of Charles Fievez (1844-1890), that the phenomenon now known as *Zeeman effect* was first observed at Brussels by Fievez.

$X^1\Sigma_g^+$) and Ballik-Ramsey ($b^3\Sigma_g^-$–$a^3\Pi_u$) systems of C_2. The medium-infrared is the domain of the fundamental vibrational bands of parent molecules, emitting through resonant fluorescence excited by the Sun (see Crovisier 1992 and references therein for a detailled discussion of this mechanism). The cometary spectra at longer wavelengths is dominated by thermal emission by the dust, over which broad bands at 10 and 18 μm, due to silicates, are conspicuous.

Table 2. Molecular bands detected in the infrared in comets.

λ μm	species	band	comet[a]	comments	references[b]
0.98	OH	v(3-0)	P/ST	ground	Toz94
1.00	OH	v(9-4)	P/ST	ground	Toz94
1.10	CN	A-X(0-0)	We, P/H	ground	Joh83 Mai87
1.21	C_2	A-X(0-0)	We	ground	Joh83
1.38	H_2O	$\nu_1 + \nu_3$	P/H	VEGA-TKS	Kra86
1.45	C_2	b-a(2-1)	We, P/H	ground	Joh83 Mai87
1.46	CN	A-X(1-2)	We, P/H	ground	Joh83 Mai87
1.78	C_2	b-a(0-0)	We	ground	Joh83
2.44	?		We, P/H	ground, unident.	Joh83 Mai87
2.7	H_2O	ν_3 group	P/H, Wi	KAO, VEGA-IKS	Mum86 Com86
2.8	X-OH		P/H...	KAO, ground	Tok87
3.0	H_2O ice		Bo, C, P/H	in absorption, tentative	
3.28	aromatics		P/H...		
3.3	CH_4	ν_3	P/H, W	ground, KAO, tentative	Kaw88 Lar88
3.3-3.5	X-CH		P/H...	many comets, unident.	
3.52	CH_3OH	ν_3	P/H...	"	
3.59	H_2CO	ν_1, ν_5	P/H	VEGA-IKS tent. ident.	Com88
4.25	CO_2	ν_3	P/H	VEGA-IKS	Com86
4.67	CO	v(1-0)	P/H, A	VEGA-IKS, ground, marginal	Com88 Dis92
6.8	X-OH ?		P/H	KAO, unident.	Bre87
10.[c]	silicates...		Be...	ground, many comets	Maa70
12.2	?		Wi	KAO, unident.	Lyn89
18.[c]	silicates...		K...	ground	Rie74
24.	?		P/H	KAO, unident.	Her87
27.	?		P/H	KAO, unident.	Her87
28.	?		P/H	KAO, unident.	Her87

[a]Full designation of comets: Be: Bennett 1970 II; K: Kohoutek 1973 XII; W: West 1976 VI; Bo: Bowell 1982 I; C: Cernis 1983 XII; P/H: P/Halley 1986 III; Wi: Wilson 1987 VII; P/ST: P/Swift-Tuttle 1992 XXVIII.

[b]Only references to first detections are given; Bre87: Bregman et al. 1987; Com86: Combes et al. 1986; Com88: Combes et al. 1988; Dis92: DiSanti et al. 1992; Her87: Herter et al. 1987; Joh83: Johnson et al. 1983; Kaw88: Kawara et al. 1988; Kra86: Krasnopolsky et al. 1986; Lar88: Larson et al. 1988; Lyn89: Lynch et al. 1989; Maa70: Maas et al. 1970; Mai87: Maillard et al. 1987; Mum86: Mumma et al. 1986; Rie74: Rieke & Lee 1974; Tok87: Tokunaga et al. 1987; Toz94: Tozzi et al. 1994.

[c]Broad feature.

Peculiarly successful high-resolution infrared observations were those of water in comets P/Halley and Wilson 1987 VII with the *Kuiper Airborne Observatory* (Mumma et al. 1986; Larson et al. 1988, 1991). Several of the ro-vibrational lines of the ν_3 band of H_2O were observed with a resolving power of 10^5. The observations were made when the comets had large velocities relative to the Earth, so that the lines were Doppler-shifted with respect to the strong telluric absorption lines. Although the resolving power was much lower than that of heterodyne techniques, the high signal-to-noise ratio of these observations permitted a measurement of the line shift due to coma asymmetries and even an attempt to deconvolve the line profiles (Larson et al. 1991).

3.2. Unidentified Features

The feature at 2.44 μm was observed in two comets. Its wavelength is too short to correspond to a fundamental vibrational band (except that of H_2). Maillard et al. (1987) proposed that it could be due to a hot band of water ($\nu_1 + \nu_3 - 2\nu_2$), but such a band would have a very small fluorescence rate. The molecular hydrogen fundamental vibrational band is near this wavelength (2.41 μm), but it is dipole-forbidden and its fluorescence rate is excessively small (2×10^{-12} s^{-1}, to be compared to a few 10^{-4} s^{-1} for allowed stretching modes of other molecules); individual H_2 ro-vibrational bands were unsuccessfully searched for in P/Halley (Smyth et al. 1989). Furthermore, H_2 is unlikely to be retained in cometary nuclei; it could result from the photolysis of cometary parent such as H_2O, but the resulting column densities are small. The most likely origin of the 2.44 μm feature is perhaps an electronic band of a radical or ion. It may be noted that the C_2H radical has bands of its $A^2\Pi$–$X^2\Sigma^+$ system in this region, but the expected fluorescence pattern of this species (as far as it is known) does not fit the observed spectrum (S. Kim *private communication*).

The feature at 2.8 μm is observed in several comets. It presumably comes from the O–H stretching mode. It may be extended at smaller wavelengths, masked by telluric absorptions by the water bands. The possible contributions of the ν_1 band and hot bands of water and of the OH radical were evaluated by Bockelée-Morvan & Crovisier (1989). Methanol (ν_1 band at 2.72 μm), other *CHO* species and the H_3O^+ ion (very strong ν_3 band at 2.84 μm) are also likely candidates. This situation needs to be clarified by space observations of the whole 2.6-2.9 μm region at high resolution.

The feature at 6.8 μm was only observed, with limited spectral resolution, in P/Halley with the KAO. Bregman et al. (1987) proposed carbonates or the C–H deformation mode of aliphatic hydrocarbons such as alkanes or alcohols. For instance, methanol has its ν_4 and ν_5 bands at this wavelength, but an abundance close to that of water would be required to explain the observed intensity. This feature could also be reasonably explained by a spike of the ν_2 band (bending mode) of water: see e.g. the water synthetic spectra computed by Bockelée-Morvan (1987).

The features in the 3.2–3.5 μm region have been a puzzle since their first detection in P/Halley. It is of little help to note that they correspond to the C–H stretching mode of organic compounds. Proposed explanations include fluorescence of small gas-phase organic molecules, thermal emission of small grains with organic mantles, emission of PAH-like molecules after transient UV heating... The best available spectra show occasionally a discrete feature at 3.28 μm (which could be the signal of aromatic compounds) and most of the time a discrete feature at 3.52 μm. The identification of the latter with the ν_3 band of methanol (Hoban et al. 1991) was prompted by the discovery of this species in significant abundances (1 to 8 % relative to water) by its radio lines (Bockelée-Morvan et al. 1991, 1994a). CH_3OH has also strong bands in the 3.30–3.45 μm region (ν_2, ν_9 and several combination bands). Attempts were

Figure 3. The spectrum of comet Levy 1990 XX in the 3 μm region. Full line: the spectrum observed at UKIRT by Davies et al. (1991). Thin line: methanol emission estimated from a simple model (Bockelée-Morvan et al.1994). Dashed line: the difference spectrum, which shows excess emission at 3.28 μm (attributed to aromatics), and at 3.32 and 3.43 μm (yet unidentified).

made to model their expected contribution to the cometary signal (Reuter 1992; Bockelée-Morvan et al. 1994c). This requires the simulation of a methanol spectrum at a rotational temperature of 50–100 K, which is very difficult due to the complexity of the methanol spectrum in this region, for which no theory is available. Another approach of the problem is to observe the spectrum of cold methanol in the laboratory. First attempts to obtain jet-cooled methanol spectra of this region with a FTS (at Giessen University, in collaboration with S. Klee, G. Mellau and A. Walters) were not successful. A high-resolution spectrum which could be recorded at 200 K is still highly congested. Further progresses on this topic could come from diode-laser spectroscopy of jet-cooled methanol. Preliminary results of the modelling definitely show, however, that methanol alone cannot explain all the cometary signal (Fig. 3). The residual emission could be explained by a few % (relative to water) of *CHO* species, but no definite identification could be proposed from the inspection of the reference spectra of simple gas-phase molecules.

Features at 12.2, 24, 27 and 28 μm have been reported. Being only spotted in a single comet, they obviously need further observations. They might be due to minerals.

4. Future Prospects

4.1. Future Observations

Cometary ions have so far only be observed in the UV or the visible. The most abundant ones: H_2O^+, H_3O^+ and CO^+ might be observable in the radio and infrared domains. Observing these ions (and especially their line shapes) could help understanding their distribution in the coma and the tail, and the chemical processes in the cometary atmosphere.

New observing facilities are being developped. From the ground, new windows in the submillimetric range are now open; more efficient infrared spectrometers are available. Fascinating prospects are expected from space projects. The *Infrared Space Observatory* is to be launched in 1995: its *Long Wavelength Spectrometer* could observe the rotational transitions of water in the 50–180 μm region; its *Short Wavelength Spectrometer*, operating longwards of 2.5 μm, could observe and resolve the rotational structure of the fundamental vibrational bands of molecules: H_2O, CO_2 and others. The 1_{10}–1_{01} water rotational line at 557 GHz is expected to be the most intense radio line in comets (Fig. 4): it could be observed with a small (1-m class antenna) submillimetre satellite such as *SWAS* (NASA project, to be launched in 1995) or *ODIN* (swedish project, in collaboration with France, Canada and Finland, to be launched in 1997). The more ambitious ESA project *FIRST*, scheduled for the beginning of next century, will be equipped with a 3-m antenna and SIS cryogenic receivers covering the submillimetre domain up to 1 THz: it could observe the fundamental rotational lines of H_2O isotopomers and of some key molecules such as ammonia.

ROSETTA is the most important project of space exploration of a comet. It will follow a periodic comet such as P/Schwassmann-Wachmann 3 or P/Wirtanen for several years at the beginning of next century. Surface modules will analyse *in situ* the surface of the nucleus. An orbiter will study *in situ* the coma gas and

Figure 4. A synthetic cometary spectrum in the millimetre-submillimetre domain. The hypothetical comet has a water prodution rate of 10^{29} molecules s^{-1}. It is observed at 1 AU from the Sun and from the Earth with a 15-m telescope. A standard composition of molecular parent molecules is assumed (Crovisier 1994), with a rotational temperature of 40 K. Most of the strong lines, besides those which are tagged, are from methanol.

dust, and monitor cometary activity by remote sensing. It will be equipped by an infrared spectrometer and possibly with a microwave spectrometer.

4.2. Laboratory Needs

The microwave spectra of most simple molecular species liable to be contained in comets are now reliably known. We are now able to observe very narrow cometary lines (cf. Fig. 1), however, and we need to know accurate frequencies and hyperfine structures. As noted above (Section 2.3), frequencies may well be better known from cometary spectra than from the laboratory. With the rapid development of radio techniques, we expect in the near future to be able to observe cometary ions and radicals. Several of them have ill-known or unknown microwave spectra (H_2O^+ for instance).

High-resolution high-sensitivity infrared cometary spectra will be soon available. These spectra are potentially very rich and likely to show the signature of several molecules of medium complexity, such as methanol (Section 3.2). We have no possibility yet to model the spectra of such molecules in cometary conditions. Important efforts will be necessary, both in laboratory work and in theoretical modelling, in order to understand in detail cometary spectra in this domain.

For the modelling of radio and infrared synthetic spectra as well as for planning observations or identifying lines, the availability of molecular spectra in the form of data bases such as *GEISA*, *HITRAN* or the *JPL Spectral Line Catalogue* is invaluable, and the diffusion of the analyses of laboratory spectra in a similar form should be encouraged.

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