



An online high resolution atlas of near-UV and optical cometary emission lines

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Introduction. Comets play a crucial role in understanding the formation and evolution of the Solar System, as they preserve the most pristine material from its early stages. Composed of rock, dust, organic material, and ices, comets release gases and dust when heated by the Sun, forming an atmosphere (coma) and characteristic tails. To advance our understanding of comets, it is essential to determine their composition and the physical processes at play and one method is the analysis of the optical spectra of their gaseous coma. At optical wavelengths, these spectra are characterized by emission lines mainly produced from fluorescence-resonance of cometary radicals, ions, and atoms which are the subproducts of the photionization and other processes acting on the larger parent molecules sublimating from the nucleus ices. Identifying correctly these lines among the forest of thousands of lines of the molecular bands at high resolution, is a first and essential step, especially as many remain unidentified despite advances in telescope technology, instrumentation, and laboratory line lists. This has motivated our team to build an atlas of cometary lines, which is a list of validated lines from high resolution and high signal to noise spectra obtained in the last two decades by the Liège team with the 8-m ESO Very Large Telescope (VLT) and covering the whole near-UV and optical range from 3040 Å to 10400 Å.

High resolution optical spectra. The most comprehensive catalog of cometary optical spectral lines until recently was that of comet 122P/de Vico, compiled by Cochran and Cochran at the McDonald Observatory and published in 2002 [1]. The observation of the bright long period comets C/2002 T7 (LINEAR) in 2004 and more recently in 2018 comet C/2016 R2 (PANSTAARS) with the high-resolution UVES spectrometer (R~100,000) coupled with the large telescope area of the VLT led to some of the best cometary optical spectra ever obtained. These spectra were reduced using the ESO UVES pipeline [2], cosmic rays were removed and SNR improved by combining several spectra taken the same night, and they were wavelength calibrated and shifted in the Earth frame, by considering the geocentric velocities. After a very careful dust continuum subtraction by small wavelength regions using the solar spectrum of Kurucz [3], as well as the removal of the telluric absorptions in the reddest part of the spectrum, we studied the cometary emission lines by developing an automatic line detection tool [4], and by identifying them using high-resolution molecular line lists found in the Exomol database [5], derived from recent fluorescence models [6, 7], or more generally found in the literature [1,4,8,9]. The sky emission line atlas observed by VLT/UVES in 2001 [10] was used to confirm the cometary nature of detected emission lines. Emission lines of CO⁺ and N₂⁺ ions were analyzed thanks to the unique spectrum of comet C/2016 R2 (PanSTARRS), because those species are much brighter in this comet compared to most of other comets [6, 7, 11].

The Cometary line Atlas. We present here a new atlas containing about 22,000 detected emission lines. Among those, approximately 75% were successfully identified as radicals (OH, NH,

S₂, CN, CH, C₃, C₂, NH₂), ions (OH⁺, CH⁺, H₂O⁺, CO⁺, N₂⁺, CO₂⁺) or atoms ([OI], [CI], [NI], NaI, FeI, NiI). The online tool allows you to check those emission lines, or the species you are interested in, for a given wavelength range, by displaying them to the high quality spectrum of comet C/2002 T7 (LINEAR), or any comet spectrum normalised and wavelength calibrated to the laboratory rest frame into the system in ascii format (wavelength; flux). With the input of the velocity of the comet with respect to the Earth (the Doppler shift) you can also check the position of the sky lines in the spectrum. Figure 1 represents a small region of the atlas, where C₂, NH₂, and unidentified lines are indicated and shows the line list and transitions information that can be retrieved as a table for the displayed spectrum.

Perspectives. A key aspect of the project involves conducting up-to-date laboratory measurements and developing models to obtain new modelled line positions for comparison with the observed spectra in order to solve the puzzle of the still thousands of lines not identified yet and improve the atlas.

Link to the online atlas. The Liège cometary line atlas can be reached on the following webpage. Comments to improve the tool are welcome.
https://www2.cometa.uliege.be/Cometary_Lineatlas

References

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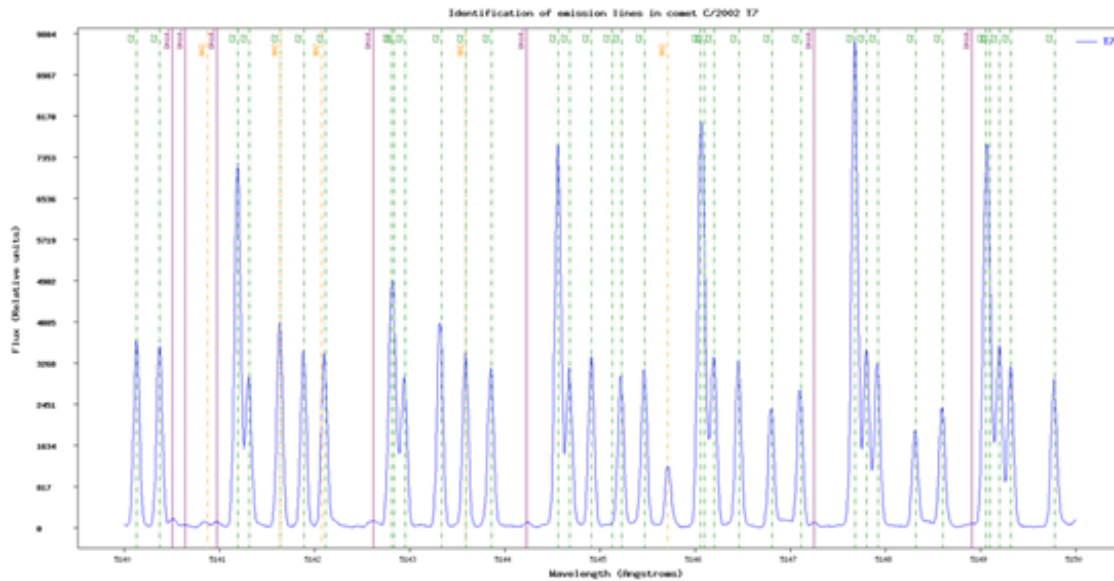


Fig.1. An example of line identifications around 5150 Å in our UVEs C/2002 T7 spectrum. bright lines are identified as C2 with a few faint NH2 and several unidentified lines.

Identification of emission lines in comets

Comets:

Minimum wavelength (Å)

Maximum wavelength (Å)

Select the species of interest

C2	C3	CH	CN	NH	NH2	OH	
<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="button" value="Check all"/>
CH+	CO+	CO2+	H2O+	N2+	OH+		<input type="button" value="Uncheck"/>
<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>		
	Atoms	Sky	Unid.				
	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>				

Maximum in Y

5140.13	C2	(Swan)	0-0	R2(13)		
5140.37	C2	(Swan)	0-0	R3(12)		
5140.50	Unid.			182		
5140.64	Unid.			60		
5140.87	NH2	A-X (0-12-0)	(0-0-0)	413 1	303 1	
5140.87	NH2	A-X (0-12-0)	(0-0-0)	413 2	303 1	
5140.97	Unid.			126		
5141.19	C2	(Swan)	0-0	P2(41)		
5141.19	C2	(Swan)	0-0	P1(42)		
5141.31	C2	(Swan)	0-0	P3(40)		
5141.64	C2	(Swan)	0-0	R1(13)		
5141.64	NH2	A-X (0-14-0)	(0-1-0)	413 2	441 2	
5141.64	NH2	A-X (0-14-0)	(0-1-0)	413 1	441 2	
5141.89	C2	(Swan)	0-0	R2(12)		
5142.07	NH2	A-X (0-14-0)	(0-1-0)	330 1	202 1	
5142.11	C2	(Swan)	0-0	R3(11)		
5142.62	Unid.			132		
5142.81	C2	(Swan)	0-0	P1(41)		
5142.84	C2	(Swan)	0-0	P2(40)		
5142.95	C2	(Swan)	0-0	P3(39)		
5143.33	C2	(Swan)	0-0	R1(12)		
5143.59	NH2	A-X (0-13-0)	(0-0-0)	643 1	735 1	
5143.59	C2	(Swan)	0-0	R2(11)		
5143.86	C2	(Swan)	0-0	R3(10)		
5144.23	Unid.			116		
5144.56	C2	(Swan)	0-0	P1(40)		
5144.56	NH2	(Swan)	0-0	P2(39)		
5144.68	C2	(Swan)	0-0	P3(38)		
5144.68	C2	(Swan)	3-4	R1(94)		
5144.91	C2	(Swan)	0-0	R1(11)		
5145.13	C2	(Swan)	1-3	R1(97)		
5145.23	C2	(Swan)	0-0	R2(10)		
5145.47	C2	(Swan)	0-0	R3(9)		
5145.71	NH2	A-X (0-12-0)	(0-0-0)	312 1	202 1	
5145.71	NH2	A-X (0-12-0)	(0-0-0)	312 2	202 1	
5146.06	C2	(Swan)	0-0	P1(39)		
5146.10	C2	(Swan)	0-0	P2(38)		
5146.20	C2	(Swan)	0-0	P3(37)		
5146.46	C2	(Swan)	0-0	R1(10)		
5146.81	C2	(Swan)	0-0	R2(9)		
5147.11	C2	(Swan)	0-0	R3(8)		