A&A 479, 257–263 (2008)
DOI: 10.1051/0004-6361:20077072

Astronomy & Astrophysics

Oxygen emission lines in the high resolution spectra of 9P/Tempel 1 following the Deep Impact event*

M. T. Capria[1], G. Cremonese[2], A. Bhardwaj[3], M. C. De Sanctis[1], and E. Mazzotta Epifani[4]

[1] INAF – Istituto di Astrofisica Spaziale (IASF), via del Fosso del Cavaliere, Rome, Italy
e-mail: mariateresa.capria@iasf-roma.inaf.it
[2] INAF – Padua Observatory, vicolo dell'Osservatorio, Padua, Italy
[3] Space Physics Laboratory, Vikram Sarabhai Space Centre, Trivandrum 695022, India
[4] INAF – Capodimonte Observatory, via Moiariello 16, Naples, Italy

Received 9 January 2007 / Accepted 12 November 2007

ABSTRACT

Context. On 2005 July 4, the NASA spacecraft Deep Impact delivered an impactor on the comet 9P/Tempel 1 to study the material ejected from the nucleus. A worldwide observation campaign accompanied the mission, to characterize the activity of 9P/Tempel 1 before and after the impact.
Aims. At La Palma (Canary Islands), the comet was observed from July 2 to July 9 using the echelle spectrograph SARG on the Telescopio Nazionale Galileo (TNG). Fifteen spectra were obtained with a resolving power of $R = 29\,000$ in the spectral range 4620–7920 Å. Many interesting emission lines can be found in this range, in particular the [OI] lines at 5577 Å ("green line") and at 6300 and 6364 Å ("red doublet "). From the analysis of these lines it is possible to derive information on the processes that produce these emissions.
Methods. The three atomic oxygen lines are clearly visible in most of the spectra. The intensity ratio between the green line and the sum of the red lines, indicative of the parent of these lines, was computed for 9 of the 15 spectra. The value of the intensity ratio for the night of July 5 was compared with the model results obtained from a coupled chemistry transport model.
Results. The intensity ratio of green to red oxygen lines obtained from the observed spectra and the one derived from the model suggest water is the main parent of the [OI] emissions on comet 9P/Tempel 1.
Conclusions.

Key words. comets: individual: 9P/Tempel 1 – comets: general

1. Introduction

On 2005 July 4 at 05:52 UT, the NASA mission Deep Impact successfully guided a copper projectile onto the comet 9P/Tempel 1 for a planned collision. The main scientific objective of the mission was to probe the interior of a comet nucleus by studying the fresh material that might be exposed by the impact.

The mission was accompanied by a worldwide observation campaign that was an integral part of the mission concept. The Jupiter-family comet 9P/Tempel 1 has a perihelion distance of 1.5 AU, an orbital period of 5.5 yr, and a rotation period of 41.85 ± 0.10 h. The comet's behavior was well characterized before the impact (Belton et al. 2005) and accurately followed during and after the event (A'Hearn et al. 2005; Meech et al. 2005; Keller et al. 2005). Analysis of the large amount of data acquired by Deep Impact, by orbiting spacecrafts, and by ground-based telescopes is still ongoing and new results are being published continuously.

From the first published results, it was clear that a crater is created, ejecting a cloud of fine powdery material moving out at a projected velocity of 5 km s^{-1} (A'Hearn et al. 2005). However, the activity triggered by the impact lasted for less than 5 days, after which the coma returned to its pre-impact state. The composition of the ejected material was different from the observed comet composition before the impact, with a much higher dust/gas ratio (Keller et al. 2005).

The images of the surface show a complex topography with at least three layers and few impact craters (Thomas et al. 2007). Water ice was found in three small patches, the extent of which was not enough to justify the observed water production: this is clear evidence that most of the volatiles are coming from below the surface (Sunshine et al. 2006; Groussin et al. 2007).

Various volatile species, besides water, were detected in the coma, before and after the impact. Of particular interest for this work are the water, CO, and CO_2 production rates during the days immediately before and after the impact. Carbon monoxide was detected both pre-impact ($4-6\times10^{27}$ molecules s^{-1}) and post-impact (1.5×10^{31} molecules) (Feldman et al. 2006). Carbon dioxide, also detected before and after the event, shows an asymmetry in the coma, being enriched with respect to water by a factor of more than 2 in the anti-sunward direction (Feaga et al. 2007). Then, CH_3OH was detected after the impact (Mumma et al. 2005).

* Based on observations collected at the Italian Telescopio Nazionale Galileo (TNG), operated on the island of La Palma by the Centro Galileo Galilei of the INAF (Istituto Nazionale di Astrofisica) at the Spanish Observatorio del Roque de Los Muchachos of the Instituto de Astrofisica de Canarias.

Article published by EDP Sciences and available at http://www.aanda.org or http://dx.doi.org/10.1051/0004-6361:20077072

Table 1. Observing conditions and oxygen lines ratios of the 15 acquired spectra.

Date	Start Time (UT)	Image ID	r (AU)[a]	Δ (AU)[b]	Projected Slit Length (km)	Red Doublet Ratio[c]	O Ratio[d]
July 2	23:45	HYRD0154	1.5063	0.8876	5150.0	2.10	0.074
July 3	21:22	HYTE0055	1.5062	0.8921	5176.1	4.60	0.056
July 3	21:53	HYTE0056	1.5062	0.8923	5177.3	2.90	...
July 3	22:24	HYTE0057	1.5062	0.8925	5178.4	3.10	...
July 4	21:08	HYWB0059	1.5062	0.8973	5206.3	2.50	0.088
July 4	21:39	HYWB0060	1.5062	0.8976	5208.0	2.40	0.087
July 4	22:11	HYWB0061	1.5062	0.8978	5209.2	2.60	0.090
July 5	21:16	HYYC0031	1.5062	0.9024	5235.9	2.25	0.100
July 5	21:47	HYYC0032	1.5062	0.9028	5238.2	2.30	0.100
July 5	22:23	HYYC0033	1.5062	0.9029	5238.8	...	...
July 5	22:54	HYYC0034	1.5062	0.9031	5239.9	...	...
July 6	21:12	HYZD0036	1.5062	0.9080	5268.4	2.50	...
July 6	21:43	HYZD0037	1.5063	0.9083	5270.1	2.60	0.080
July 6	22:14	HYZD0038	1.5063	0.9085	5271.3	2.30	...
July 9	21:05	HZDB0012	1.5069	0.9246	5364.7	2.38	0.130

[a] Heliocentric distance. [b] Geocentric distance. [c] Intensity ratio of the two red lines. [d] Intensity ratio of the green to the sum of the two red lines.

Water production rate was measured by ground-based (Mumma et al. 2005; Schleicher et al. 2006) and space-based instruments, such as OSIRIS on Rosetta (Kueppers et al. 2005; Keller et al. 2006) and the Submillimeter Wave Astronomy Satellite (SWAS) (Bensch et al. 2006). In the days before and after the impact, the water production rate varied, alternating between periods of higher activity and periods of lower outgassing. It ranged, following the above cited papers, from 0.5 to 2.0×10^{28} molecules s^{-1}, with a tendency toward the higher side after the impact.

A series of outbursts were detected (A'Hearn et al. 2006), almost all of them probably correlated with the rotation of the nucleus; the last one was observed on July 2 at 8:34 UT, nearly 12 h before the beginning of the observations described in this paper. Another possible cause for observed outbursts is an increase in the solar wind flux (Willingale et al. 2006). This phenomenon seems to be short-lived (less than few hours), so it was probably not affecting the observations reported here.

2. Observations and data reduction

In the framework of the worldwide observation campaign, the comet was observed with the high resolution spectrograph SARG (Gratton et al. 2001) mounted on the 3.5 m Telescopio Nazionale Galileo (TNG) in the island of La Palma (Spain). The comet was observed for 6 nights, July 2 to July 9, 2005. In order to characterize the behavior of the comet and look for possible changes in the coma composition as a consequence of the impact, two of the observation nights were planned immediately before the impact and the other ones after the impact (see Table 1).

SARG is a cross-dispersed echelle spectrograph simultaneously covering the wavelength range between 3700 and 10 000 Å; a selection of 6 slits and 4 grisms is available. During entire observation nights, 15 spectra were acquired using an exposure time of 1800 s and the same setup: a slit with 1.60×8.0 arcsec (0.30×1.5 mm) and a grism were used covering the spectral range of 4590–7920 Å on the mosaic of two CCDs, providing a resolving power of $R = 29\,000$. The projected length of the slit on the comet varied from 5150 km to 5365 km (see Table 1).

The data were reduced using the IRAF ECHELLE package, following standard procedures. The spectrum of the brilliant star HR4963 (tetVirHD114330), spectral type $A1IV$, was used to facilitate the extraction of comet spectra. The data along the slit length were summed, obtaining 15 one-dimensional spectra of 55 orders each (34 on the blue chip, from 4590 to 6162 Å, and 21 on the red chip, from 6220 to 7920 Å). A thorium lamp was used for the wavelength calibration. By fitting the thorium line position for all the orders of each spectrum, dispersion solutions were achieved with rms errors generally lower than 10 mÅ. The only exception was the spectrum acquired on July 6: due to a very bad thorium lamp image, it was impossible to calibrate the blue part of two of the three spectra acquired during that night. After the wavelength calibration, all spectra were Doppler shifted and divided by the continuum as a final step in the reduction process.

To have an idea about the quality of data, one can look at panels a, b, and c of Fig. 1 where it is possible to see the order 20 from the red chip (6290–6360 Å) in three spectra taken on different nights, July 2, 4, and 9. Emission lines at corresponding wavelengths in all the three nights are clearly identifiable.

3. Data analysis

In the visible part of the electromagnetic spectrum, between 4590–7920 Å, numerous emission lines can be found, most of them originating from the "fragment" species such as NH_2, C_2, CN, and so on. A high resolution spectrum is usually crowded with lines, often more or less blended, depending on the level of activity of the comet. In this part of the spectrum there is also a large number of unidentified lines, among which even undetected species could be hidden, and most of these unidentified lines can be attributed to probably unknown transitions of NH_2 and C_2.

We have been performing a long-term observation program aimed at the study of these unidentified lines (Cremonese et al. 2007). High resolution spectra with SARG were obtained for four other comets: the aim is to catalogue emission lines, look for unidentified lines, compare them on the different comets and possibly identify them. In a recent paper (Cremonese et al. 2007) on a spectrum of the comet 153P/Ikeya-Zhang, observed in April 2002 at a higher resolution ($R = 57\,000$) when it had a distance of 0.89 AU from the Sun and 0.43 AU from the Earth, 8469 emission lines were catalogued, 1862 of which

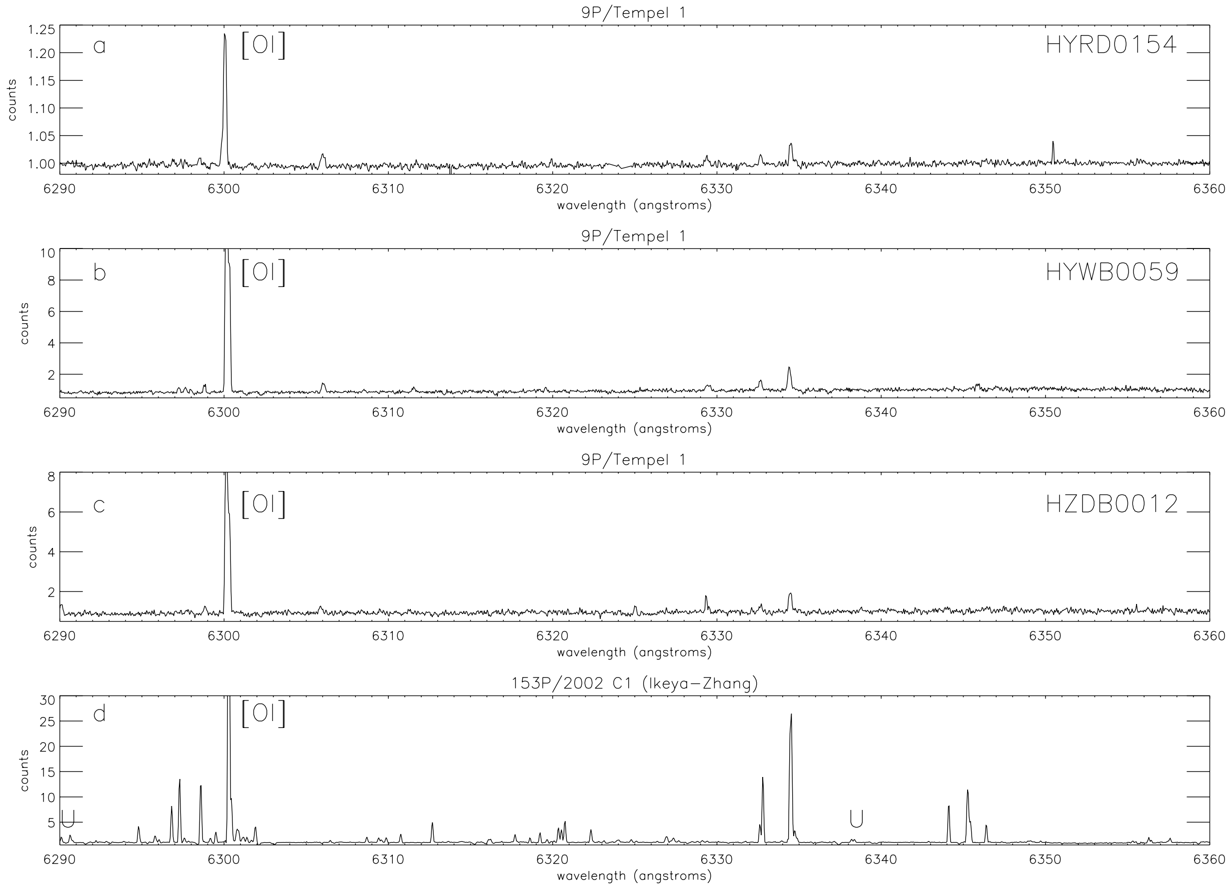

Fig. 1. Spectra of 9P/Tempel 1 and 153P/Ikeya-Zhang, range 6290–6360 Å. **a)** 9P/Tempel 1, July 2; **b)** 9P/Tempel 1, July 4; **c)** 9P/Tempel 1, July 9; **d)** 153P/Ikeya-Zhang: "U" means unidentified line; the other lines visible in this spectrum can be attributed to NH_2.

were unidentified. These unidentified lines are already listed in other similar catalogues (Brown et al. 1996; Zhang et al. 2001; Cochran & Cochran 2002), but we have also found unidentified emission lines that are not listed in the catalogues cited above. All these unidentified lines are still being analyzed and will be the subject of a future paper. This catalogue will help us to identify the emission lines on spectra acquired with lower resolution: this is the case, for example, for 9P/Tempel 1, which at the time of observation was farther from the Sun and less active than the 153P/Ikeya-Zhang. One of the orders extracted from the observed spectrum of this comet is shown in panel d of Fig. 1: it is in the same wavelength range of the spectra as for the three nights of 9P/Tempel 1 (shown in the panels a, b, and c). The difference in the number of emission lines and their intensity are clearly visible. The most prominent line is the atomic O line; two weak lines marked by "U" are listed as unidentified in two published catalogues (Cremonese et al. 2007; Cochran & Cochran 2002). All other lines detectable in panel d can be attributed to NH_2. A comparative analysis of the emission lines in all the spectra of 9P/Tempel 1 is ongoing and the results will be published in a later paper.

4. Analysis of the atomic oxygen emission lines

In the visible part of a cometary spectrum that has enough spectral resolution, three important emission lines of atomic oxygen can be detected: the green line at 5577.339 Å (^{1}S–^{1}D) and the forbidden red oxygen doublet at 6300.304 and 6363.776 Å (^{1}D–^{3}P) (Feldman et al. 2004). The [OI] lines cannot be produced by solar resonance fluorescence excitation of the ground-state oxygen atom, but instead represent a "prompt emission", which means that they can be produced directly in the excited states by photodissociation of the parent molecule. Ninety-five percent of oxygen atoms excited in the ^{1}S state decay to the ground ^{3}P state via the ^{1}D state, while 5% of them decay directly to the ground state. This means that if the green line is present the red doublet is always present, while the opposite is not always true.

There are many reactions that can produce these forbidden oxygen lines (Bhardwaj & Haider 2002). However, not all of them involve the water molecule. They can also involve, for example, CO and CO_2.

The question of the origin of O lines is interesting. If it can be assumed that water is the main source of these lines, the O column density can be used to deduce the H_2O production rate (see, for example, Morgenthaler et al. 2001; Morgenthaler et al. 2007). Moreover, since the lifetime of the ^1D state at 1 AU is $\sim$110 s, much shorter than the corresponding lifetime of a water molecule ($\sim 8\times10^4$ s at 1 AU) (Crovisier 1994), the red emission lines are a good tracer of the distribution of water molecules in the cometary coma, because they cannot travel far without decaying.

One or more of these oxygen lines have been detected in several comets (see for example Fink & Johnson 1984; Magee-Sauer et al. 1990; Schultz et al. 1993; Morrison et al. 1997; Cochran 1984; Cochran & Cochran 2001; Zhang et al. 2001; Morgenthaler et al. 2001; Capria et al. 2005; Morgenthaler et al. 2007), but their unambiguous detection, especially that of the green line at 5577 Å, is a non-trivial task. Firstly, the high

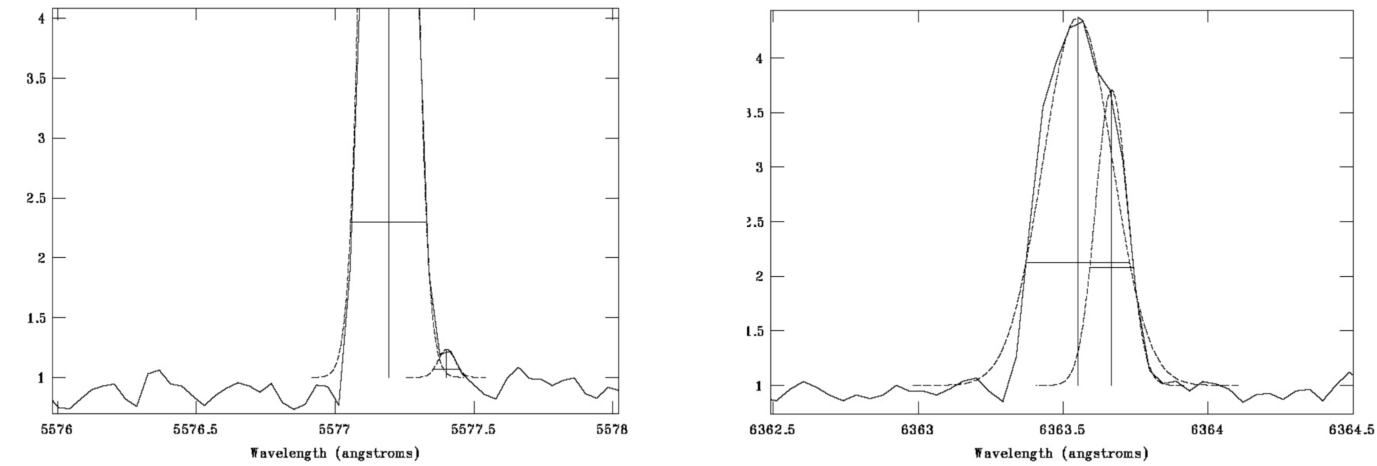

Fig. 2. Telluric (on the *left*) and cometary (on the *right*) oxygen lines for 2 nights of observation, July 2 and 3. The units of the vertical axis are arbitrary. The decomposition of the two blended lines, fitted with a Gaussian line profile, is shown. On the *left*: spectrum HYRD0154, line at 5577 Å. On the *right*: spectrum HYTE0057, line at 6363 Å.

spectral resolution is necessary to distinguish the three lines from usually strong telluric O emission lines. Secondly, the red line at 6300 Å is very close to the Q branch of a NH_2 band, and the green line at 5577 Å is in the middle of a crowded C_2 band ((1,2) P-branch).

In most spectra that we have acquired at TNG, the O emission lines, though blended with strong telluric lines, are clearly visible. In the Figs. 2–4 six of these lines, one per night of the observation, are plotted; the cometary line is on the right, blended with the more intense telluric line. The cometary and telluric lines are 0.2 Å apart, so they can be resolved ("deblended") without difficulty. The C_2 emission lines are very weak in all the spectra.

The comparison of line intensities on different nights is potentially very interesting but is beyond the scope of this paper, so it will be discussed in a forthcoming paper when the flux calibration of all spectra is completed.

4.1. The ratio of the atomic O lines

The intensity ratio of the two red lines can give a preliminary idea of the quality of data, because it can be tested with respect to its theoretical value, 3.027 (Storey & Zeippen 2000).
The intensity $I(R)$ of an emission line can be written as (Festou & Feldman 1981)

$$I = 10^{-6}\,\tau_{\rm p}^{-1}\,\alpha\,\beta\,N$$

where τ_p is the dissociative lifetime of the parent, α the yield of photodissociation, β the branching ratio, and N the column density of the parent molecule. In the case of a red doublet, the ratio of two line strengths should be the same as the ratio of their branching ratios, because they are both transitions from the $(2p^4)\,^1D$ state to the $(2p^4)^3P$ ground state. The value of this ratio has been computed for all spectra, except two, of 9P/Tempel 1, and is listed in the seventh column of Table 1 and plotted in Fig. 5 (upper panel).

The intensity ratio of the green to the sum of the two red lines is more interesting, because it provides a clue to the identity of the parent molecule(s) of O atoms in the cometary coma. In the case of the green to red intensity ratio we can write (Cochran & Cochran 2001):

$$\frac{I_{5577}}{I_{6300}+I_{6364}} = \frac{\tau_{\rm green}^{-1}\alpha_{\rm green}N_{\rm green}\beta_{5577}}{\tau_{\rm red}^{-1}\alpha_{\rm red}N_{\rm red}(\beta_{6300}+\beta_{6364})}$$

and, if we assume that there is only one parent, the column densities are almost the same. The effective excitation ratio for dissociation of a parent molecule is proportional to $\tau^{-1}\ \alpha\,\beta$. Festou & Feldman (1981) have computed the theoretical value of this ratio for three different molecules (see Table 2): is 0.1 in the case of H_2O and 1 in the case of CO_2 and CO[1].

We computed this ratio for all the calibrated spectra in which the three cometary lines are visible and separable from the telluric lines: the spectrum taken on July 2, one of the spectra taken on July 3, the spectra taken on July 4, 2 of the spectra taken on July 5, one of the spectra of July 6, and the one spectrum of July 9. The values obtained are listed in the eighth column of Table 1 and plotted in Fig. 5 (bottom panel). Below follows a more detailed discussion about the atomic oxygen lines in the acquired spectra (Figs. 2–4) and the two ratio values: the intensity ratio of the two red lines (from now on ratio 1) and intensity ratio of the green to the sum of the two red lines (from now on ratio 2).

July 2, 2005 All three lines can be seen in the only spectrum of this night, HYRD0154. The green line is shown in Fig. 2, plot on the left. Ratio 1 result is somewhat lower than the corresponding results for the other nights.

July 3, 2005 The green line can be seen in only one spectrum, HYTE0055; in other two spectra neither the cometary nor the telluric green lines can be seen. Because of this, the ratio 2 has been computed only for the spectrum HYTE0055. The result of ratio 1 for the spectrum HYTE0055 is higher than the theoretical value, close to 3, for unclear reasons (possibly a contamination?). It is probable that this result, and consequently also the ratio 2 for this same spectrum, should be discarded. The values of ratio 1 for the spectra HYTE0056 and HYTE0057 (Fig. 2, line at 6363 Å, plot on the right) are close to the theoretical value.

[1] Recently, Huestis & Slanger (2006) have questioned the validity of some of the photodissociation yields found in the literature and used in this paper; at the moment, lacking further information, we are using these values.

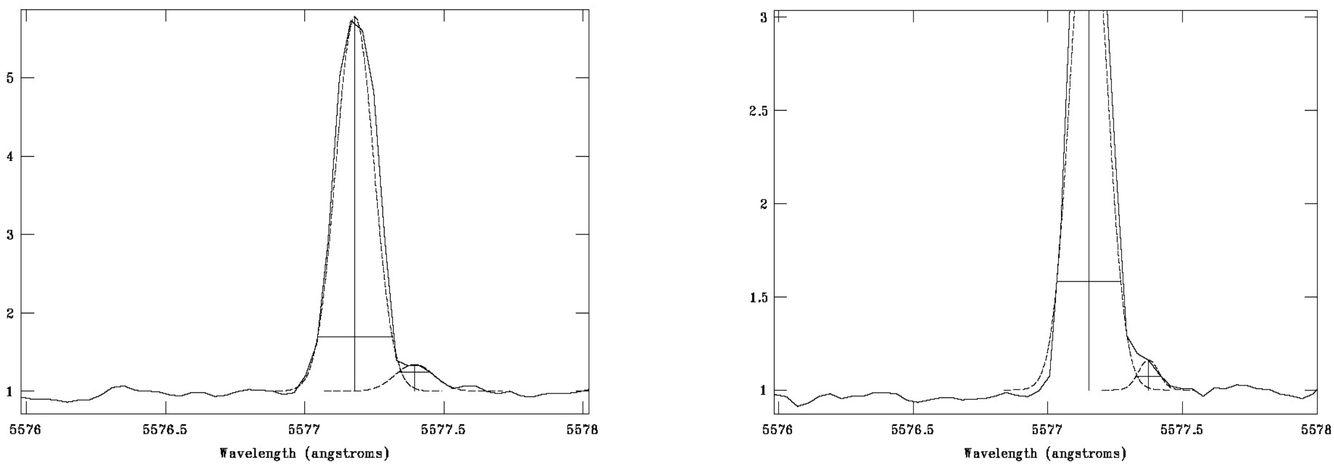

Fig. 3. Telluric (on the *left*) and cometary (on the *right*) oxygen lines for 2 nights of observation, July 4 and 5. The units of the vertical axis are arbitrary. The decomposition of the two blended lines, fitted with a Gaussian line profile, is shown. On the *left*: spectrum HYWB0061, line at 5577 Å. On the *right*: spectrum HYYC0033, line at 5577 Å.

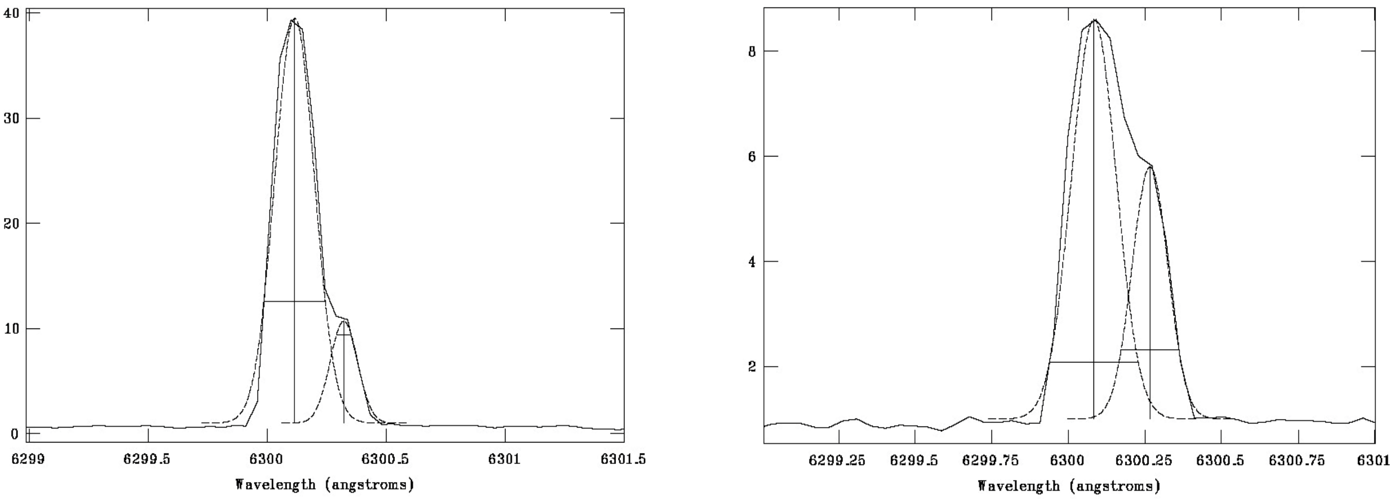

Fig. 4. Telluric (on the *left*) and cometary (on the *right*) oxygen lines for 2 nights of observation, July 6 and 9. The units of the vertical axis are arbitrary. The decomposition of the two blended lines, fitted with a Gaussian line profile, is shown. On the *left*: spectrum HYZD0037, line at 6300 Å. On the *right*: spectrum HZDB0012, line at 6300 Å.

July 4, 2005 Green and red lines can be distinguished and the ratios can be computed for all three spectra. In Fig. 3, plot on the left, the 5577 Å line of spectrum HYWB0061 is shown. The three values obtained for ratio 1 are consistent and seem to be reasonably close to the theoretical value like the values computed for ratio 2.

July 5, 2005 In spectra HYCC0033 (Fig. 3, plot on the right, line at 5577 Å) and HYCC0034, the red cometary lines cannot be distinguished from the telluric lines, so ratio values have not been computed. For spectra HYYC0031 and HYYC0032, ratio values have been computed and the ratio 2 is the same for both spectra, while the ratio 1 is lower than the theoretical value of 3.027 (Storey & Zeippen 2000).

July 6, 2005 Due to a malfunctioning thorium lamp, the blue part of the spectrum was been calibrated for only one spectrum, HYZD0037, in which the green line is clearly visible. The red lines can be distinguished in all spectra and give acceptable values for the ratio 1; the ratio 2 has been computed only for HYZD0037. In Fig. 4, the line at 6300 Å for the spectrum HYZD0037 can be seen on the left.

July 9, 2005 In the only spectrum of this night, HZDB0012, both ratios were computed; ratio 1 is not far from its theoretical value. In Fig. 4, on the righthand side, the line at 6300 Å can be seen.

In Fig. 5 all computed values of ratio 1 (upper panel) and ratio 2 (bottom panel) have been plotted with respect to UT. The ratio 1 value ranges from 2.1 to 4.6 ± 0.1. If we exclude the two extreme values on the either side, which correspond to spectra HYRD0154 and HYTE0055, all values are in reasonable agreement with the theoretical value of 3.027 given by Storey & Zeippen (2000). The computed value for ratio 2 (Fig. 5, bottom panel) ranges from 0.056 to 0.13 ± 0.1 and seems to follow an increasing trend towards the end of the observation period. It should be noted, at any rate, that if we discard the ratio values for spectra HYRD0154 and HYTE0055, due to the "quality" of data given by the ratio 1, we have no values for dates preceding the impact; as a consequence, it is very difficult to look for differences in values before and after the Deep Impact event.

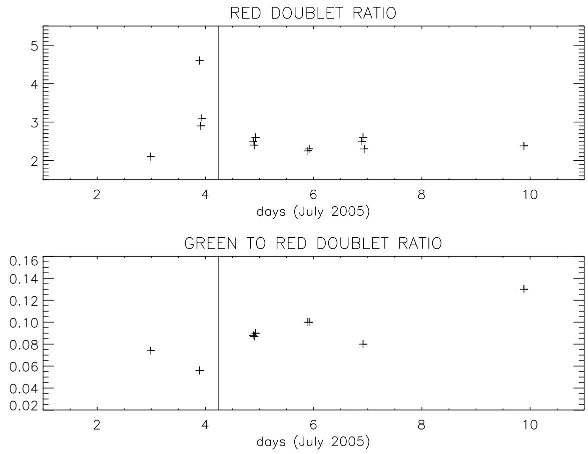

Fig. 5. a) Values of the ratio of the red doublet (ratio 1) computed from the spectra acquired on the nights from July 2 to July 9; **b)** atomic oxygen emission ratio values (ratio 2) computed from the spectra acquired on the nights from July 2 to July 9. The vertical line shows the time of Deep Impact event.

Table 2. Theoretical value of the ratio O(^{1}S)/ O(^{1}D) (from Festou & Feldman 1981).

Parent	Ratio O(^{1}S)/ O(^{1}D)
H_2O	0.1
CO_2	1
CO	1

The values we obtained for the ratio 2 can be compared with the theoretical values derived by Festou & Feldman (1981) for three molecules, shown in Table 2. Comparing the value listed in the last column of Table 1 with those in Table 2, it is clear that the computed values for ratio 2 obtained from our spectra are consistent with the production of O atoms predominantly from the H_2O dissociation.

5. A theoretical model of the atomic oxygen lines production

The observational results of the oxygen green to red line ratio can be compared with the model results obtained from a coupled chemistry transport model (Bhardwaj et al. 1996; Bhardwaj 1999; Haider & Bhardwaj 2005). The model accounts for attenuation of the solar radiation and EUV-generated photoelectrons in the cometary coma (Bhardwaj et al. 1990; Bhardwaj 2003). The chemistry of O(^{1}D) atoms is given in Bhardwaj & Haider (2002). This model has already been applied to the analysis of the atomic oxygen lines observed in a spectrum of the comet 153P/ Ikeya-Zhang (see Capria et al. 2005, where some details of the model are given). The major source of the production of metastable O-species in the inner coma is the dissociation of H_2O, while the major loss processes are quenching (collision reaction with H_2O) and radiative de-excitation (Bhardwaj & Haider 2002).

Since during observations the comet 9P/Tempel 1 was at heliocentric distance of 1.5 AU (which means more than a factor of 2 fall in solar flux than that at 1 AU), and with an order of magnitude lower gas production rate, the average O line brightness at comet 9P/Tempel 1 was weaker than that at comet 153P/Ikeya-Zhang observed with the same telescope in April 2002 (Capria et al. 2005).

Model calculations were been performed for the July 5 observation, taking the H_2O gas production rate of 2×10^{28} molecules/s and CO abundance as 4.5% of water (Mumma et al. 2005). In the absence of direct measured abundance of CO_2, its value is taken as 3% (similar to what was used for comet 153P/Ikeya-Zhang). The O-bearing parent molecule CH_3OH is assumed to have an abundance of 1%; other O-bearing molecules do not directly affect the chemistry of O(^{1}D) and O(^{1}S) and hence the O red and green lines ratio. Because of the lower gas production rate ($Q \simeq 2 \times 10^{28}$ molecules/s), the cometary coma is optically thin for the solar EUV radiation, resulting in essentially incomplete attenuation of the solar EUV-soft X-ray flux, and it can travel to the nucleus (Bhardwaj 2003). Following the method of calculating oxygen red (6300 and 6363 Å) and green (5577 Å) line emissions (Bhardwaj & Haider 2002; Bhardwaj et al., in preparation), we derive the ratio of the intensities of the green to red lines. Using this model the calculated value is 0.1 (±0.02). This value is in good agreement with what we obtained on July 5. A similar reasoning could be applied for the other nights of observation. The agreement between the model and observation suggests that water was the main source of oxygen atoms on comet 9P/Tempel 1.

Table 1 shows that the value of the intensity ratio of O lines varied between 0.06 and 0.13. This variation could be due to the low activity of comet during the observation, which even resulted in the rotation of comet seen in the lightcurve of X-rays from this comet as observed by the Chandra X-ray Observatory (Lisse et al. 2005; Bhardwaj et al. 2007). This could also mean that solar wind penetration could be deeper in the coma (due to low Q value) and can influence the O line ratio by electron impact dissociation and ionization.

6. Discussion and conclusion

From the spectra acquired at TNG during the Deep Impact event epoch, we obtained the intensity ratio of the green to the sum of two red lines for days following the impact, from July 4, 21:08 UT to July 9, 21:05 UT. The values obtained from these observations are consistent with the production of O atoms predominantly from the H_2O dissociation.

The conclusion obtained for the comet 9P/Tempel 1 is similar to what was obtained for 153P/Ikeya-Zhang (Capria et al. 2005). The two comets were observed at heliocentric distances at which the main driver of the activity is water. The first observation of 9P/Tempel 1 began 15 h after the impact, when the activity triggered by the impact had mostly subsided.

Some of the [OI] lines from 9P/Tempel 1 during the impact event were detected and analyzed by other observers. Manfroid et al. (2007) acquired several high-resolution spectra with the VLT Ultra Violet Echelle Spectrograph (UVES) in the days immediately following the impact, and extracted and investigated the rotational lightcurves during the hours immediately following the impact and the phase diagram of [OI] (5577 and 6300 Å). Since model fitting of the observed curve requires a 3-step dissociation sequence, they concluded that probably [OI] (^{1}S) atoms are produced through OH or CO, and not directly from the dissociation of H_2O or CO_2. They also noted that the [OI] and OH lightcurves are different, and suggest that this could indicate a significant contribution from the dissociation sequence of CO_2. They also concluded that the material releasing the [OI] seems to be present for a longer period than when releasing the other species. A direct comparison with our results, however, cannot be made, because our first spectrum after the impact was

Table 3. Oxygen lines ratio in the literature.

Comet[a]	$\frac{I_{5577}}{I_{6300}+I_{6364}}$	r (AU)[b]	△ (AU)[c]
C/Iras-Araki-Alcock (1)	0.022–0.034	1.02	...
C/1996 B2 Hyakutake (2)	0.12–0.15	1.083–1.002	0.120–0.119
C/1995 O1 Hale-Bopp (3)	0.22–0.18	0.920–0.991	1.322–1.627
C/1999 S4 LINEAR (4)	0.06 ± 0.01	0.97–0.79	1.21–0.45
153P/Ikeya-Zhang (5)	0.12 ± 0.1	0.89	0.43
9P/Tempel 1 (this work)	0.056−0.13 ± 0.1	1.5	0.9

[a] References. (1) Cochran (1984); (2) Morrison et al. (1997); (3) Zhang et al. (2001); (4) Cochran & Cochran (2001); (5) Capria et al. (2005).
[b] Heliocentric distance. [c] Geocentric distance.

acquired at 21:39 UT, while the above-cited spectra cover the time range from 5:36 and 9:11 UT.

Hodapp et al. (2007) observed the comet during the nights of July 2 to July 9 from the University of Hawaii Telescope. Using spectra obtained with the Supernova Integral Field Spectrograph (SNIFS) these authors studied the spatial distribution and temporal evolution of the [OI] emission at 6300 Å. They conclude that immediately after the impact the [OI] flux raised by a factor of 3, but then declined, and after three days it was at pre-impact level. In this case a direct comparison between our observation and those obtained by these authors, immediately after the impact, is also not possible. However, both results from observations on the following nights agree well.

The observations described in this work are not the first measurements of the intensity ratio between the green and the red doublet lines of atomic oxygen in the comets. Table 3 presents this ratio for other comets, along with heliocentric and geocentric distances of the comet at the observation time and the corresponding bibliographic reference.

It can be seen from Table 3 that the measurements obtained point to the water as the only, or at least the dominant, parent of atomic O lines. However, the set of measured ratios is not representative, because all the ratios refer to comets at a heliocentric distance close to 1 AU, where it is well known that water ice sublimation is the main driver of the activity and the sublimated water constitutes the major part of the cometary gas. This reasoning also applies to comet 9P/Tempel 1: even if the gas production was enhanced by the contribution of fresh material, as it seems by the results of observation (Mumma et al. 2005; Keller et al. 2005), it has been always dominated by water. It would be very interesting (but very difficult) to measure the ratio of green to red atomic O lines at a point along the cometary orbit where the sublimated water (and its products) is not the major constituent of the gaseous coma. We believe that at such times this ratio can be different from those shown in Table 3. We see from Table 3 that the highest ratio (≃0.2) was obtained for the comet Hale-Bopp. A possible reason is that the CO abundance with respect to water in this comet was quite high (≃12% at the nucleus, and ≃23% with the coma-extended source effect) (Bockelée-Morvan et al. 2004). As can be noted from Table 2, the ratio of green to red lines will tend towards unity with an increasing abundance of CO and CO_2 relative to the water.

Acknowledgements. Observations at TNG have been partially funded by the Fundación Galileo Galilei of the INAF (Istituto Nazionale di Astrofisica).
We would like to thank A. Magazzú for his valuable help during the nights of observation.

References

A'Hearn, M. F., Belton, M. J. S., Delamere, W. A., et al. 2005, Sci, 310, 258
A'Hearn, M. F., et al. 2006, BAAS, 4, 37
Belton, M. J. S., Meech, K. J., A'Hearn, M. F., et al. 2005, Space Sci. Rev., 117, 137
Bensch, F., Melnick, G. J., Neufeld, D. A., et al. 2006, Icarus, 184, 602
Bhardwaj, A. 1999, J. Geophys. Res., 104, 1929
Bhardwaj, A. 2003, Geophys. Res. Lett., 30(24), 2244
Bhardwaj, A., & Haider, S. A. 2002, Adv. Space Res., 29(5), 745
Bhardwaj, A., Haider, S. A., & Singhal, R. P. 1990, Icarus, 85, 216
Bhardwaj, A., Haider, S. A., & Singhal, S. P. 1996, Icarus, 120, 412
Bhardwaj, A., Elsner, R. F., Gladstone, G. R., et al. 2007, Planet. Space Sci., 55, 1135
Bockelée-Morvan, D., Crovisier, J., Mumma, M. J., & Weaver, H. A. 2004, The composition of cometary volatiles, in Comets II, ed. M. C. Festou, U. Keller, & H. A. Weaver, Univ. Arizona Press, Tucson, 2004
Brown, M. E., Bouchez, A. H., Spinrad, H., & Johns-Krull, C. M. 1996, AJ, 112, 1197
Capria, M. T., Cremonese, G., Bhardwaj, A., et al. 2005, A&A, 442, 1121
Cochran, W. D. 1984, Icarus, 58, 440
Cochran, A. L., & Cochran, W. D. 2001, Icarus, 154, 381
Cochran, A. L., & Cochran, W. D. 2002, Icarus, 157, 297
Cremonese, G., Capria, M. T., & De Sanctis, M. C. 2007, A&A, 461, 789
Crovisier, J. 1994, J. Geophys. Res., 99, 3777
Feaga, L. M., A'Hearn, M. F., Sunshine, J. M., et al. 2007, Icarus, 190, 345
Feldman, P. D., Cochran, A. L., & Combi, M. R. 2004, Spectroscopic investigation of fragment species in the coma, in Comets II, ed. M. C. Festou, U. Keller, & H. A. Weaver, Univ. Arizona Press, Tucson
Feldman, P. D., Lupu, R. E., McCandliss, S. R., et al. 2006, ApJ, 647, L61
Festou, M. C., & Feldman, P. D. 1981, A&A, 103, 154
Fink, U., & Johnson, J. R. 1984, AJ, 89(10), 1565
Gratton, R. G., Bonanno, G., Bruno, P., et al. 2001, Exper. Astron., 12, 107
Groussin, O., A'Hearn, M. F., Li, J.-Y., et al. 2007, Icarus, 187, 16
Haider, S. A., & Bhardwaj, A. 2005, Icarus, 177, 196
Hodapp, K. W., Aldering, G., Meech, K. J., et al. 2007, Icarus, 187, 185
Huestis, D. L., & Slanger, T. G. 2006, DPS ♯38, ♯62.20, American Astronomical Society
Keller, H. U., Jorda, L., Küppers, M., et al. 2005, Science, 310, 281
Keller, H. U., Kueppers, M., Fornasier, S., et al. 2006, Icarus, 187, 87
Kueppers, M., Bertini, I., Fornasier, S., et al. 2005, Nature, 437, 987
Lisse, C. M., Christian, D. J., Dennerl, K., et al. 2005, ApJ, 635, 1329
Magee-Sauer, K., Roesler, F. L., Scherb, F., et al. 1990, Icarus, 84, 154
Manfroid, J., Hutsemekers, D., Jehin, E., et al. 2007, Icarus, 187, 144
Meech, K. J., Ageorges, N., A'Hearn, M. F., et al. 2005, Science, 310, 265
Morgenthaler, J. P., Harris, W. M., Scherb, F., et al. 2001, ApJ, 563, 451
Morgenthaler, J. P., Harris, W. M., & Combi, M. R. 2007, ApJ, 657, 1162
Mumma, M. J., Di Santi, M. A., Magee-Sauer, K., et al. 2005, Sci, 310, 270
Morrison, N. D., Knauth, D. C., Mulliss, C. L., et al. 1997, PASP, 109, 676
Schleicher, D. G., & Birch, P. V. 2002, BAAS, 34, 853
Schleicher, D. G., Barnes, K. L., & Baugh, N. F. 2006, AJ, 131, 1130
Schultz, D., Li, G. S. H., Scherb, F., et al. 1993, Icarus, 101, 95
Storey, P. J., & Zeippen, C. J. 2000, MNRAS, 312, 813
Sunshine, J., A'Hearn, M. F., Groussin, O., et al. 2006, Science, 311, 1453
Thomas, P. C., Veverka, J., Belton, M. J. S., et al. 2007, Icarus, 187, 4
Willingale, R., O'Brien, T., Cowley, S. W. H., et al. 2006, ApJ, 649, 541
Zhang, H. W., Zhao, G., & Hu, J. Y. 2001, A&A, 367, 1049