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Forbidden oxygen emission lines in optical high-resolution spectrum of 21P/Giacobini-Zinner in 2018 apparition

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Abstract

Forbidden emission lines emitted form excited oxygen atoms at 557.7 nm (from $O(^1S)$ to $O(^1D)$) and at 630.0/636.4 nm (from $O(^1D)$ to $O(^3P)$) have been used to estimate water gas production rates of comets, and also recently used for CO_2/H_2O abundance ratio in comets. Here we report optical high-resolution spectroscopic observations of comet 21P/Giacobini-Zinner taken by HDS mounted on the Subaru Telescope atop of Maunakea, Hawaii. Thanks to very weak C_2 Swan band emission in this comet, we could observe the forbidden oxygen emission line at 557.7 nm without strong contamination by C_2 lines. The forbidden red lines of oxygen atom at 630.0/636.4 nm could also been detected clearly. The green-to-red line ratio of the comet indicates relatively low abundance ratio of CO_2 with respect to H_2O.

1. Introduction

Forbidden oxygen emission lines [O I] at 557.7 nm and at 630.0/636.4 nm are usually observed in optical spectra of comets [3-11]. Those green (557.7 nm) and red lines (630.0/636.4) lines are emitted from excited state of oxygen atoms that are produced at photodissociation of water and oxygen-bearing molecules in cometary coma. The green line from $O(^1S)$ to $O(^1D)$ is usually weaker than red lines from $O(^1S)$ to $O(^3P)$. The green-to-red line ratio (G/R ratio) is typically in the range of 0.09 ± 0.02 for heliocentric distances smaller than 2 au [5]. Based on model calculations [1,2], the G/R ratio is considered as a clue to CO_2/H_2O mixing ratio in comets. Since the initial attempt to derive CO_2/H_2O ratio from G/R ratio in comet 116P/Wild 4 at 2.4 au from the Sun [7] several comets have been observed at relatively far from the Sun (> 2 au) and they exhibited higher G/R ratios than typical value (0.09 ± 0.02); i.e., more abundant in CO_2 compared to H_2O [6,8,10].

2. Observations

We observed comet 21P/Giacobini-Zinner (hereafter, G-Z) to search for $^{15}NH_2$ in the comet on UT 2018 September 5, 9 and October 3 by the HDS spectrograph and the Subaru Telescope atop of Maunakea, Hawaii. The spectral resolution was 72,000 and the slit size was 9" x 0".5 on the sky. Total exposure time was 281,000 s on source. Here we focus on the spectrum taken on October 3 when the relative velocity of the comet relative to observer is -10.5 km s^{-1} (large enough to separate telluric and cometary oxygen emission lines). In comet 21P/G-Z, C_2 and NH_2 are strongly depleted and their emission lines were very weak (both C_2 and NH_2 emission lines usually contaminate the forbidden oxygen emission lines). Especially, the green line is significantly contaminated with C_2 emission lines in many cases. Therefore, comet 21P/G-Z is one of best targets for investigating forbidden oxygen lines in comets.

3. Results and Discussion

The G/R ratio (defined as the flux ratio of the green line to the red lines) in comet 21P/G-Z is derived as 0.07, corresponding to the column densities ratio of CO_2/H_2O = 4.8% from the equation (12) of [5] (we don't assume quenching of forbidden oxygen emission lines [1,2]). The derived CO_2/H_2O abundance ratio indicates that comet 21P/G-Z is depleted in CO_2 compared to other comets.

We also measured the intrinsic line width of forbidden oxygen emission for both the green and the red lines. The intrinsic FWHM of [O I] at 557.7 nm is 3.53 ± 0.05 km s^{-1} while the intrinsic FWHMs of [O I] at 630/646.3 nm are 1.64 ± 0.03 and 1.77 ± 0.03 km s^{-1}, respectively. As already demonstrated by previous studies [3,4,5], the intrinsic FWHM of the green line (~2 – 3 km s^{-1}) is wider than those of the red lines (~1 – 2 km s^{-1}). The G/R ratio in the case that H_2O molecules mainly produce the excited oxygen atoms is 0.04 while the G/R ratios are 0.60 and 0.78 in the cases of CO_2 and CO, respectively [5]. Decock et al. claimed that CO_2 is the best candidate to explain wider line width for the green line because the excitation source of $O(^1S)$ from CO_2 is more energetic (around 95.5 – 116.5 nm) than that of $O(^1S)$ from H_2O (the Ly-α photons at 121.6 nm) [5]. However, this is not always correct. The excess energy at the photodissociation can accelerate the products as follows, in the case of AB + photon → A + B:

$$hc/\lambda - D - I = \frac{1}{2}m_{\mathrm{A}}v_{\mathrm{A}}^2 + \frac{1}{2}m_{\mathrm{B}}v_{\mathrm{B}}^2 \qquad (1)$$

where λ is the wavelength of photon that photodissociates the parent molecule (like H_2O and CO_2), *D* is dissociation energy of the parent, *I* is the energy imparted to the internal degrees of freedom of the photodissociation fragments (A and/or B), v_{A} and v_{B} are the speeds of the fragments in the center of momentum reference frame, and m_{A} and m_{B} are the masses of the fragments, respectively. Even for more energetic photons, the final velocities depend on both *D* and *I*.

Alternatively, we considered the collisional quenching for $O(^1D)$ atoms in coma. If the energy represented by the left-band side of equation (1) is similar for both $O(^1D)$ and $O(^1S)$, $O(^1D)$ can be accelerated to a similar speed as $O(^1S)$, immediately after the photodissociation of its parent molecule. Because the lifetime of $O(^1D)$ is longer than $O(^1S)$ by a factor of ~100, the probability of collision between $O(^1D)$ and H_2O (as background) is larger than that for $O(^1S)$. Therefore, $O(^1D)$ atoms with larger relative velocities to the surrounding coma flow are selectively removed from the coma by collisions. Eventually, $O(^1D)$ atoms with similar velocity vectors as the background coma (i.e., ~1 km s^{-1}) remain. This mechanism can play important role to realize narrower line width for the red lines, especially in a productive comet (the come gas density is higher) and less effective for comets far from the Sun. We will present the results based on the collisional Monte-Carlo simulations for $O(^1D)$ and $O(^1S)$ in the case of comet 21P/G-Z and discuss about the validity of the above hypothesis.

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