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Evolution of H_2O, CO, and CO_2 production in Comet C/2009 P1 Garradd during the 2011–2012 apparition ☆

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ABSTRACT

We present analysis of high spectral resolution NIR spectra of CO and H_2O in Comet C/2009 P1 (Garradd) taken during its 2011–2012 apparition with the CSHELL instrument on NASA's Infrared Telescope Facility (IRTF). We also present analysis of observations of atomic oxygen in Comet Garradd obtained with the ARCES echelle spectrometer mounted on the ARC 3.5-m telescope at Apache Point Observatory and the Tull Coude spectrograph on the Harlan J. Smith 2.7-m telescope at McDonald Observatory. The observations of atomic oxygen serve as a proxy for H_2O and CO_2. We confirm the high CO abundance in Comet Garradd and the asymmetry in the CO/H_2O ratio with respect to perihelion reported by previous studies. From the oxygen observations, we infer that the CO_2/H_2O ratio decreased as the comet moved towards the Sun, which is expected based on current sublimation models. We also infer that the CO_2/H_2O ratio was higher pre-perihelion than post-perihelion. We observe evidence for the icy grain source of H_2O reported by several studies pre-perihelion, and argue that this source is significantly less abundant post-perihelion. Since H_2O, CO_2, and CO are the primary ices in comets, they drive the activity. We use our measurements of these important volatiles in an attempt to explain the evolution of Garradd's activity over the apparition.

1. Introduction

1.1. Primary ices in comets

Cometary activity is driven by the sublimation of H_2O, CO_2, and/or CO ice present in the nucleus. H_2O is thought to be the primary driver of activity when comets are closer to the Sun than about 3 AU, though there are exceptions such as 103P/Hartley where CO_2 is the main driver (A'Hearn et al., 2011). At larger heliocentric distances, more volatile species (CO_2 and/or CO) are the primary drivers, and their sublimation is often invoked to explain distant activity in comets (e.g. C/1995 O1 Hale-Bopp, which exhibited a coma until it reached a heliocentric distance of 28 AU (Szabó et al., 2012)). However, the transition between H_2O and CO_2/CO driven activity in comets is poorly understood.

In addition to being the main drivers of cometary activity, H_2O, CO_2, and CO are typically the most abundant ices present in cometary nuclei. The relative abundances of these ices in cometary nuclei can reveal details of their formation and evolutionary history. There is still much debate in the literature whether the abundances of CO and CO_2 in comets reflect thermal evolution of cometary nuclei (Belton and Melosh, 2009) or whether the observed compositions reflect formation conditions (A'Hearn

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et al., 2012). The formation of CO_2 likely occurs via grain surface interactions of OH and CO, though this reaction is not completely understood (A'Hearn et al., 2012, and references therein). Therefore knowledge of the CO and CO_2 abundances in comets is paramount for creating a complete picture of cometary composition and differentiating between the effect of formation conditions and subsequent thermal evolution on cometary composition.

Both H_2O and CO can be observed from the ground in the NIR, while CO is also observable from ground-based sub-mm observations. Lacking a dipole moment, CO_2 has only been observed through its ν_3 vibrational band at 4.26 μm, which is heavily obscured by the presence of telluric CO_2 and therefore cannot be observed from the ground. This has led to a paucity of observations of this important molecule. Before 2004, the CO_2 abundance had been measured for only a few comets (Combes et al., 1988; Crovisier, 1997). Observations in the past 10 years by space-based platforms such as Spitzer (Pittichová et al., 2008; Reach et al., 2009, 2013) and AKARI (Ootsubo et al., 2012), as well as observations obtained with the Deep Impact spacecraft (Feaga et al., 2007, 2014; A'Hearn et al., 2011), have resulted in a nearly ten-fold increase in the number of comets with known CO_2 abundances and have emphasized the importance of CO_2 in comets. Spitzer is the only one of these IR observatories still in operation, but it is reaching the end of its operational lifetime. The launch of the James Webb Space Telescope (JWST) in 2018 will reenable observations of CO_2 in comets, but not all comets in the inner Solar System will be observable due to elongation angle and non-sidereal tracking constraints. In any case, the limited time available on space-based platforms (as opposed to ground-based telescopes) severely limits the study of CO_2 in comets. Therefore a ground-based proxy for CO_2 production in comets is of fundamental importance.

1.2. Atomic oxygen as a proxy

Atomic oxygen is a photodissociation product of H_2O, CO_2, and CO, and therefore can serve as a viable proxy for these species. Specifically, observations of the forbidden oxygen lines at 5577, 6300, and 6364 Å can reveal the mixing ratios CO_2/H_2O and CO/H_2O in comets. Past studies have used [O I]6300 emission to obtain indirect estimates of the H_2O production rate for many comets (Spinrad, 1982; Magee-Sauer et al., 1990; Schultz et al., 1992; Morgenthaler et al., 2001, 2007; McKay et al., 2012, 2014). Depending on the wavelength of the dissociating photon, photodissociation of H_2O, CO_2, and CO can result in the release of an O I atom in an excited state, either ^1S or ^1D. These excited oxygen atoms then radiatively decay through the 5577 Å line (^1S) or 6300 and 6364 Å lines (^1D).

The O I atoms will be preferentially released into the coma in either the ^1S or ^1D state depending on the identity of the parent molecule. Water releases $O(^1S)$ oxygen at a rate that is 3–8% of the rate for releasing $O(^1D)$, whereas for CO_2 and CO the rate of $O(^1S)$ release upon photodissociation is 30–90% of the $O(^1D)$ release rate (Delsemme, 1980; Festou and Feldman, 1981; Bhardwaj and Raghuram, 2012). These relative efficiencies are reflected in the ratio of the line intensities (hereafter referred to as the "oxygen line ratio"), given by

$$R \equiv \frac{N(O(^1S))}{N(O(^1D))} = \frac{I_{2972} + I_{5577}}{I_{6300} + I_{6364}} \quad (1)$$

where $N(x)$ denotes the column density of the species x and I_y denotes the intensity of line y. In the past calculations of the oxygen line ratio using Eq. (1) have ignored the 2972 Å line due to it being much fainter than the other lines (10% of the 5577 Å line (Slanger et al., 2011)) and not being observable from the ground. As our observations are not sensitive to this line, we will follow this practice when calculating the oxygen line ratios presented in this work. For sufficiently low number densities where collisional quenching is insignificant, the oxygen line ratio will never be greater than 1, because every atom that decays through the 5577 Å line will subsequently decay through the 6300 Å or 6364 Å line. This is illustrated in Fig. 1, which shows the energy level diagram for O I. Therefore a ratio of 0.03–0.08 suggests that H_2O is the dominant parent, whereas a ratio of 0.3–0.9 implies that the primary parent molecule is CO_2 or CO (Delsemme, 1980; Festou and Feldman, 1981; Bhardwaj and Raghuram, 2012). This is a qualitative way of assessing the dominant parent of O I, and has been employed in the past to show that the dominant parent is H_2O (Cochran and Cochran, 2001; Cochran, 2008; Capria et al., 2002, 2008). Recently, it has been suggested that the oxygen line ratio can be used to infer the CO_2/H_2O ratio in comets, provided that the physics responsible for the release of O I is understood (McKay et al., 2012, 2013; Decock et al., 2013).

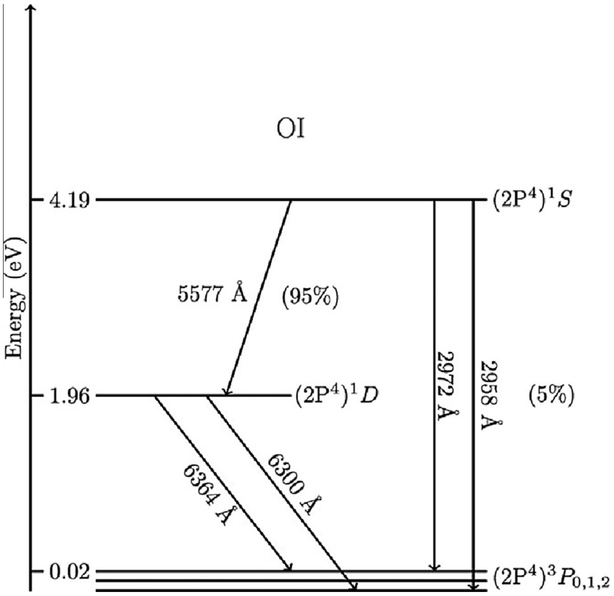

Fig. 1. Energy level diagram for O I. Note that all oxygen atoms that radiatively decay through the 5577 Å line then subsequently decay through either the 6300 Å or 6364 Å line. Image credit Bhardwaj and Raghuram (2012).

We present analysis of high resolution NIR and optical spectroscopy of Comet C/2009 P1 (Garradd) (hereafter Garradd) obtained during its 2011–2012 apparition. We employ the NIR spectra to obtain production rates of H_2O and CO, and the optical spectra to infer the CO_2 and H_2O abundance from analysis of the oxygen lines. The paper is organized as follows. In Section 2 we describe our observations, reduction and analysis procedures. Section 3 presents our CO, CO_2, and H_2O production rates and caveats to be considered when interpreting CO_2/H_2O ratios inferred from the oxygen line ratio. In Section 4 we discuss the implications of our results for the volatile activity of Garradd. Section 5 presents a summary of our conclusions.

2. Observations and data analysis

We obtained data on Garradd using three instruments and facilities. We acquired NIR spectra of Garradd for studying CO and H_2O using the CSHELL instrument mounted on the NASA Infrared Telescope Facility (IRTF) on top of Maunakea, Hawaii. We obtained most of the optical spectra of Garradd for studying atomic oxygen with the ARCES echelle spectrometer mounted on the Astrophysical