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The molecular composition of Comet C/2007 W1 (Boattini): Evidence of a peculiar outgassing and a rich chemistry

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ABSTRACT

We measured the chemical composition of Comet C/2007 W1 (Boattini) using the long-slit echelle grating spectrograph at Keck-2 (NIRSPEC) on 2008 July 9 and 10. We sampled 11 volatile species (H_2O, OH^*, C_2H_6, CH_3OH, H_2CO, CH_4, HCN, C_2H_2, NH_3, NH_2, and CO), and retrieved three important cosmogonic indicators: the ortho-para ratios of H_2O and CH_4, and an upper-limit for the D/H ratio in water. The abundance ratios of almost all trace volatiles (relative to water) are among the highest ever observed in a comet. The comet also revealed a complex outgassing pattern, with some volatiles (the polar species H_2O and CH_3OH) presenting very asymmetric spatial profiles (extended in the anti-sunward hemisphere), while others (e.g., C_2H_6 and HCN) showed particularly symmetric profiles. We present emission profiles measured along the Sun–comet line for all observed volatiles, and discuss different production scenarios needed to explain them. We interpret the emission profiles in terms of release from two distinct moieties of ice, the first being clumps of mixed ice and dust released from the nucleus into the sunward hemisphere. The second moiety considered is very small grains of nearly pure polar ice (water and methanol, without dark material or apolar volatiles). Such grains would sublimate only very slowly, and could be swept into the anti-sunward hemisphere by radiation pressure and solar-actuated non-gravitational jet forces, thus providing an extended source in the anti-sunward hemisphere.

1. Introduction

Comets are among the best-preserved bodies in the Solar System. Their ices have witnessed a multifaceted formation history in the solar nebula. As comets enter the inner Solar System their ices sublimate, releasing into the expanding coma parent volatiles that then are observable at infrared wavelengths through fluorescence. Cometary fluorescence is driven by solar radiation that pumps the molecules into excited vibrational states. They subsequently emit infrared photons through rapid decay to the ground vibrational state in a direct fashion (resonant fluorescence), or through branching into intermediate vibrational levels (non-resonant fluorescence). Collisions are ineffective in exciting these states owing to the low densities and temperatures prevalent in cometary atmospheres. With powerful infrared high-resolution spectrometers these intense fluorescent spectral lines can be measured with high sensitivity, and when combined with new analytical methods we now can characterize the chemical composition (production rates, isotopic and isomeric ratios, ortho-para ratios, etc.) of comets with unprecedented precision.

Do all these indicators reveal a similar and static formation environment for pre-cometary ices, or do they reflect a more dynamic and continuously evolving formation process? Particularly interesting is whether comets from different dynamical reservoirs (Kuiper Belt, Oort Cloud) shared a common formation path. Recent dynamical models strongly suggest that considerable mixing occurred in the formation region, and thus that comets in a given reservoir originated from diverse regions of the proto-planetary disk. The diversity and fractional representation of sub-populations in each reservoir might differ, making them useful for testing predictions of dynamical models (Mumma and Charnley, 2011).

Differences in formation region should be imprinted in the properties of individual comets. Strong compositional diversity of parent volatiles is emerging, but with as yet no unique relationship

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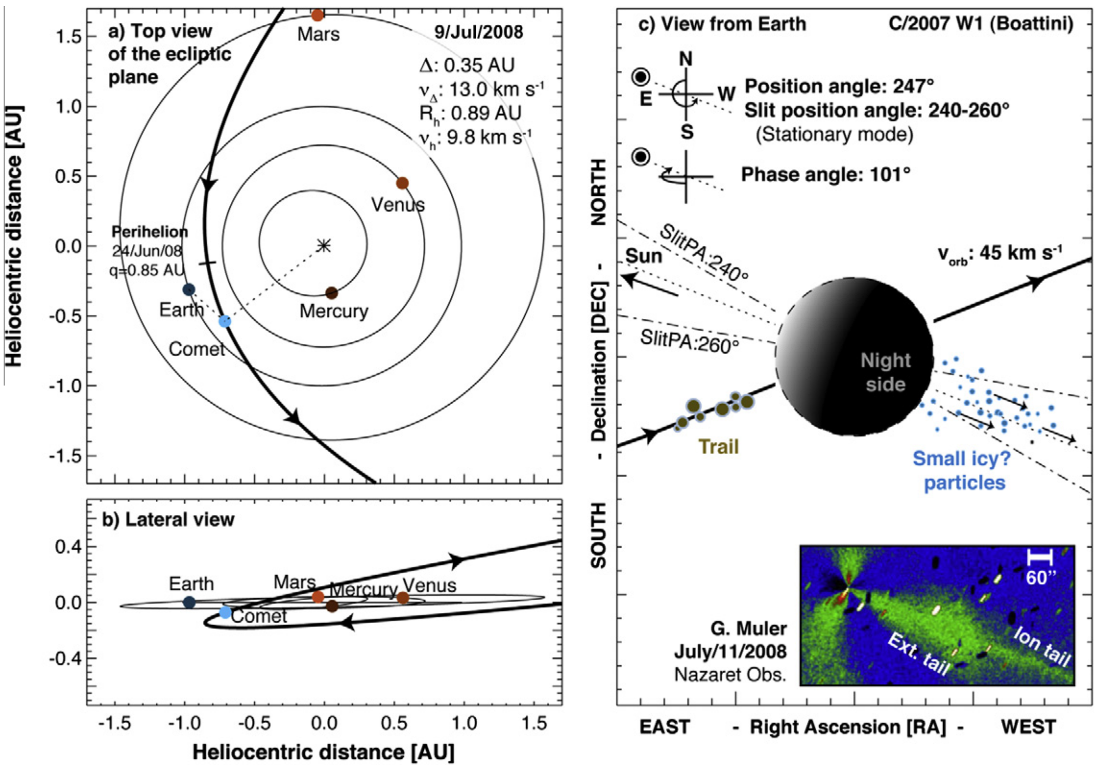

Fig. 1. Diagrams showing the position and orbit of the comet (panels 'a' and 'b') during the observations in July 2008, with panel 'c' presenting the projection as observed from Earth. The observations were performed just after perihelion, and the instrument slit was oriented along the Sun–comet radius vector projected onto the sky plane. In panel 'c' we include an image of comet Boattini taken by Gustavo Muler on July/11/2008 using the Nazaret Observatory (Lanzarote, Spain) with a clear optical filter, processed using the Larson–Sekanina numerical approach (rotational shift difference) to enhance anisotropic excesses. The image shows a narrow ion tail and an emission 'cloud' (distinct from the narrow ion tail) extended in the anti-sunward direction. Small icy particles are preferentially affected by solar pressure and solar-actuated non-gravitational jet forces leading to a possible enhancement of these particles in the anti-sunward direction. Solar wind pickup of charged icy grains could also be at work beyond the ionopause.

to dynamical class or inferred reservoir of origin. For instance the two comets showing the most depleted organic chemistry, C/1999 S4 (Mumma et al., 2001) and 73P/SW 3 (Villanueva et al., 2006; DiSanti et al., 2007a; Dello Russo et al., 2007; Kobayashi et al., 2007), come from the Oort Cloud and Kuiper Belt reservoirs respectively. At the other extreme, the two comets showing particularly rich organic chemistry, 17P/Holmes (Dello Russo et al., 2008) and C/2001 A2 (Magee-Sauer et al., 2008), come from the Kuiper Belt and Oort Cloud respectively.

These observational discoveries – in concert with new insights obtained through dynamical modeling of transport in the early Solar System – indicate a more complex scenario in which both principal comet reservoirs (Kuiper Belt and Oort Cloud) contain bodies formed in diverse regions of the protoplanetary disk (Morbidelli et al., 2005). We emphasize, however, that the fractional representation of each type (enriched, depleted) within a given comet reservoir is as yet poorly constrained, owing to the small number (~20) of comets characterized to date at infrared wavelengths. Every additional comet so characterized represents a precious addition to this expanding database and, as the third comet found to be enriched in organic primary volatiles, C/2007 W1 provides an excellent demonstration of this added value.

Comet C/2007 W1 (Boattini) – hereafter Boattini – re-entered the inner Solar System for the first time after residing for billions of years in the Oort Cloud (OC), making it dynamically new (Nakano, 2008). Discovered by Andrea Boattini through the Mount Lemmon survey in 2007 when it was at (heliocentric distance) 3.3 AU, this comet reached perihelion (0.85 AU) and closest approach to Earth (0.21 AU) in June 2008. This unusually favorable placement produced visual magnitudes around 5 in June–July 2008, making it a very favorable target (Fig. 1).

In this paper, we present infrared spectral observations sampling 11 volatile species (H_2O, OH^*, C_2H_6, CH_3OH, H_2CO, CH_4, HCN, C_2H_2, NH_3, NH_2, CO) in comet Boattini. We report the

Table 1
Observing log.

Date (UT)	Time (UT)	Setting	Molecules sampled	R_h (AU)	v_h (km s^{-1})	Δ (AU)	Δ-dot (km s^{-1})	AM	Slit PA (°)	Comet PA (°)
July 9 2008	14:18 14:47	KL1	H_2O, CH_3OH, C_2H_6, CH_4	0.893	9.77	0.348	12.91	1.97	241–248	248
	14:54 15:32	KL2	H_2O, H_2CO, CH_4, HCN, C_2H_2, NH_3	0.893	9.79	0.348	12.96	1.52	250–261	248
July 10 2008	14:18 14:31	MWA	H_2O, CO	0.898	10.34	0.356	12.92	1.94	242–246	248
	14:42 15:27	KL1	H_2O, H_3OH, C_2H_6, CH_4	0.899	10.36	0.356	12.98	1.51	248–261	248

The ephemeris values are given for the midpoint of the time interval, where R_h is the heliocentric distance of the comet, v_h is the heliocentric velocity of the comet, Δ is the geocentric distance, Δ-dot is the topocentric velocity, PA indicates "position angle" and AM indicates "airmass".