An Interferometric Study of CO and CS in Comet Hale-Bopp (C/1995 O1)

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Abstract. We used the BIMA Array to observe CO and CS molecules in Comet Hale-Bopp (C/1995 O1) during the 1997 apparition. A spur-like structure around the cometary nucleus is observed. These molecular spurs may be attributed to gas or dust jets. Using Haser model, we find the theoretically predicted CO scale length agrees well with observations. A large fraction of CO is sublimated directly from the nucleus, with the remaining CO coming from icy dust grains in cometary coma. The [CO/H_2O] abundance ratio of Hale-Bopp is consistent with that of icy dust grains in star forming regions. We conclude that Hale-Bopp was likely formed at the stage when there were still ample of icy grains in Solar Nebula; therefore, abundances of parent molecules in a comet may reflect the primordial chemical composition of the Nebula.

1. Introduction

Comets are thought to have their chemical compositions preserved from pristine interstellar material in Solar Nebula. However, individual comets are known to be different from one another sometimes. By comparing cometary chemical abundances with interstellar medium in star-forming regions, we will better understand the origin of comets, the physical conditions and chemical compositions of the primordial Nebula, and the formation of our solar system accordingly. In addition, study of cometary compositions will also provide us important clues to the physical and chemical evolution of parent molecular clouds, which form planetary systems eventually. The contemporary view is that much of the organic material required to initiate the Earth's prebiotic chemistry was delivered by cometary and asteroidal impacts (e.g., Chyba et al. 1990). Perhaps this is one of the most profound reasons to study comet for its possible connection with the origin of life in our solar system; nevertheless, such a relation between comets and life is yet to be proven by direct observational evidence.

2. Observations and Results

Comet Hale-Bopp was observed at 115.27 GHz (CO J=1-0) and at 97.98 GHz (CS J=2-1) using the BIMA (Berkeley-Illinois-Maryland Association) Array
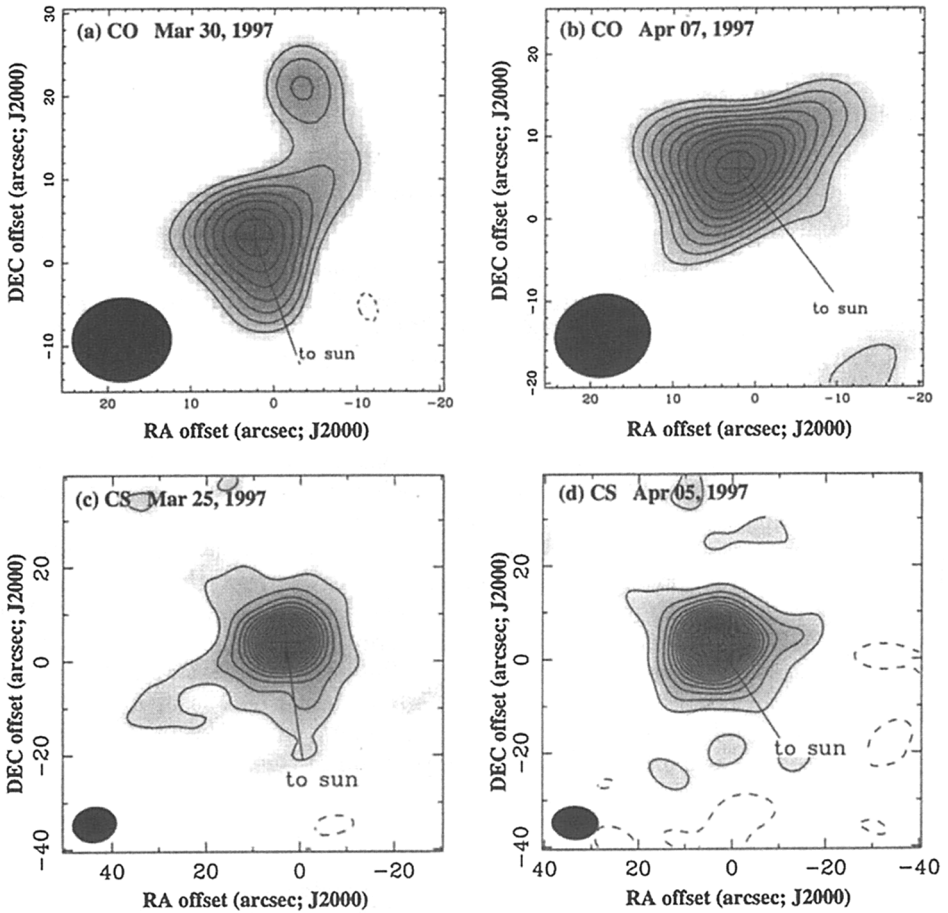
Figure 1.   The integrated-intensity maps of CO and CS

from March 25 to April 7 during the 1997 apparition. Figure 1 shows the integrated intensity maps of CO [Figs. 1(a) & (b)] and CS (Figs. 1(c) & (d)) of Hale-Bopp. The gas production rate, Q, is a measure of how many molecules of certain species are leaving the cometary surface per second. The typical gas production rate (at 1 AU) of water is $Q \simeq 10^{30}\,s^{-1}$, for example. Considering photodissociation when molecules are exposed to solar UV radiation, the *Haser model* attempts to derive the column densities, N in cm^{-2}, of the parent and daughter molecules of a comet. Haser model is particularly useful for an icy halo surrounding the comet nucleus, such as in the case that parent molecular emission extends well beyond the photodissociation scale length (Λ_p) when parent molecules are sublimated from both the comet nucleus and surfaces of dust grains in the halo. Assuming a spherical cometary nucleus releasing parent molecules at a constant outflow velocity, v, and the photodissociation rate is directly proportional to the number of parent molecules, we have the Haser

model for parent molecules:

$$N_p(a) = \frac{Q}{2\pi v} e^{r_n/\Lambda_p} \int_0^\infty \frac{e^{-\sqrt{a^2+z^2}/\Lambda_p}}{a^2 + z^2} d_z \qquad (1)$$

where r_n is the radius of the nucleus, z is the linear scale along the line of sight and a is the impact parameter. Comparisons of Haser model images with the actual molecular emission observed (Fig. 1) allow us to test whether CO is a parent molecule or not. Figure 2 shows the Haser-model subtracted CO difference maps of Hale-Bopp. Little is left in the residual maps after model-image subtraction except the northwestern component seen in the image on March 30 (Fig. 2(a)) and a couple of $\lesssim 3$-σ components of excess-emission. The northwestern component is in the direction of the dust tail which indicates a minority of CO gas toward the comet might be sublimated from icy dust grains in the comet halo; alternatively, though less likely, these CO molecules may be in fact daughter molecules produced via photodissociation of other parent molecules. The overall agreement between the observed CO emission and Haser model strongly suggests CO is a parent molecule coming primarily from the comet nucleus. Cometary CO abundance, therefore, may well reflect the primordial abundance of the primitive Solar system bodies. The theoretically predicted photodissociation scale length of CO (Huebner et al. 1992) is also confirmed by the rather *clean* difference maps. The observed column density at 1 AU is 2.31×10^{16} cm^{-2} for CO, and 2.32×10^{14} cm^{-2} for CS; the gas production rates thus derived are $Q = 3.56 \times 10^{30}$ s^{-1} and 4.03×10^{28} s^{-1} of CO and CS, respectively. A [CO/H$_2$O] abundance ratio of ~ 0.36 is obtained, based on the H$_2$O production rate measured by Dello Russo et al. (2000); and for [CS/H$_2$O], ~ 0.004.
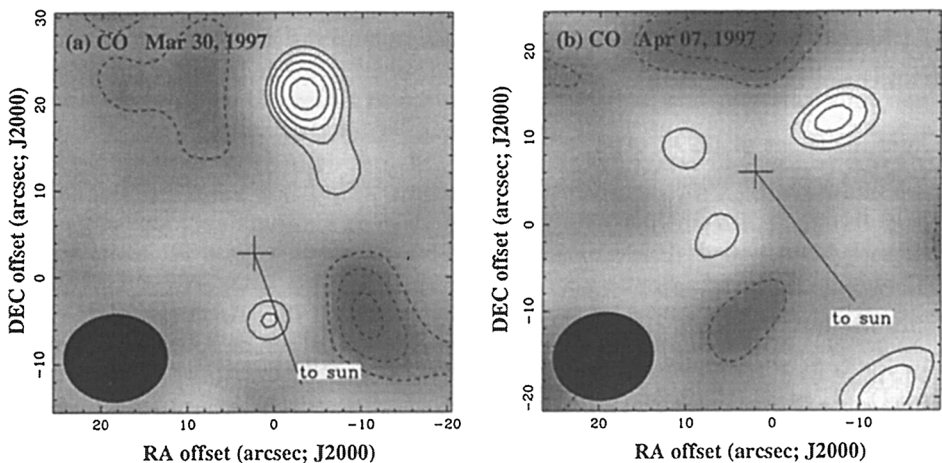

Figure 2. Haser-model subtracted CO difference maps. The excess emission (the positive residuals shown in solid contours) is attributed to CO sublimated from surfaces of icy dust grains in the comet halo.

3. Discussions

The [CO/H_2O] abundance ratio derived is consistent with that measured by DiSanti et al. (1999; ~0.24). When compared to other comets, the abundance ratio of Hale-Bopp (Period $\gtrsim$ 3000 years) is similar to that of other long-period comets (P > 200 years), such as ~0.43 (Womack et al. 1997) and ~0.3 (Lis et al. 1997) of Comet Hyakutake (P ~20,000 years); and is a factor of 2 higher than that of Comet Halley (P = 76 years; Eberhardt et al. 1987). However, the [CO/H_2O] ratio is significantly higher than that of short-period comets (P < 200 years, excluding Halley-family comets). For example, Comet 21P/Giacobini-Zinner (P = 6.61 years) has a ratio of only ~0.02-0.03 (Weaver et al. 1999), and Comet 103P/Hartley 2 (P = 6.3 years), $\leq$0.01 (Weaver et al. 1994). Both Comet G-Z and 103P/Hartley 2 are of Jupiter-family comets. The large difference of [CO/H_2O] ratios between long-period and short-period comets may be largely due to the fact that long-period comets are from Oort cloud but short-period ones were formed in Kuiper Belt. However, various chemical evolution experienced by individual comets may also play an important role on the difference found.

When compared to interstellar medium (ISM), the [CO/H_2O] ratio of Hale-Bopp is comparable to that of ISM measured in solid-phase via IR observations. An abundance ratio of ~0.18 was measured towrad high-mass YSO, RAFGL 7009S (Ehrenfreund et al. 1997); likewise, ~0.12 in NGC 7538 IRS 9 (Whittet et al. 1996). A ratio of 0.30 was reported in the low-mass YSO, R CrA IRS1 (Chiar et al. 1998). Nonetheless, the abundance ratios observed in gas-phase in hot molecular cores, ~30 in Orion hot core (Knacke & Larson 1991) and ~4000 in Sgr B2(N) (Sutton et al. 1991), are significantly higher. It suggests that the [CO/H_2O] ratios of Hale-Bopp and interstellar icy dust grains are quite similar. This strongly indicates that some comets, at least for the long-period ones, were formed when a large quantity of icy dust grains from the parent cloud were still preserved in the Nebula.

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