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Observations of comets with the Large Millimeter Telescope *Alfonso Serrano*

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Abstract. The composition of the volatile ices in comets provides important contraints on models of the formation of the solar system. Millimeter-wave observations of comets, from ground-based telescopes, provide a means to measure the molecular composition of the ices through observations of gas produced by sublimation of the comet. Ground-based observational campaigns of many comets with the Large Millimeter Telescope *Alfonso Serrano* will allow characterization of variations in the composition of the ices from comet to comet and searches for new molecular species.

Key words. Solar System: Comets

1. Introduction

Comets are important to the study of the Solar System because the material in their nuclei has not been altered extensively since its formation. Millimeter-wave observations of comets offer the opportunity to make direct measurements of the composition of the cometary ices by observing molecular lines in the coma of the comet. In this paper, we describe the contribution that millimeter-wave observations with the Large Millimeter Telescope *Alfonso Serrano* (LMT) may be expected to make now that the telescope is completed.

Comets owe their spectacular appearance to the sublimation of volatile ices in the cometary nucleus as it is heated when it approaches the Sun. The dominant cometary volatile is water, but observations of comets, both remote and in situ by the *Rosetta* Spacecraft, have revealed many 10's of other volatile species. In addition to the volatile ices, comets are also observed to release non-volatile material, generally refered to as "dust". This material is lifted from nucleus as a result of the sublimation of ices.

The existence of volatile ices provides evidence that the nucleus has not been strongly heated since its origin. For example, the recent detection of N_2 (Rubin et al. 2015) and Ar (Balsiger et al. 2015) in Comet P67/Churyumov-Gerasimenko during the *Rosetta* Mission indicates that the comet cannot have been heated above the sublimation temperatures of theses ices ($\sim$ 20-25K). Thus, the material in the nucleus is unlikely to have been heated and altered since the time of its formation, and the comets that exist today are artifacts that provide a record of conditions in the past.

Comet composition is also of interest to the study of the Earth. Impacts of comets with the Earth in the past probably delivered cometary

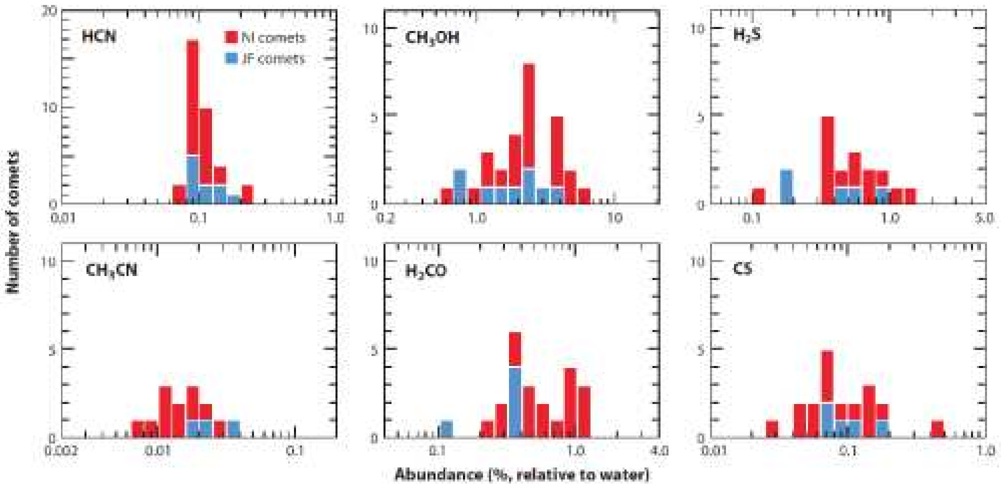

Fig. 1. Histogram of abundances of molecules in several comets. Comets from the Oort Cloud (red; labeled NI in figure) and from the Jupter Family (blue; labeled JF) are distinguised. The figure shows that some species are quite variable from comet to comet. There are no obvious correlations of these trends with origin from the Oort Cloud or Jupiter Family. Figure from Mumma & Charnley (2011)

volatile materials onto the terrestrial surface. It is interesting to consider whether significant amounts of water could have been delivered in this way. It is also worth considering the role that complex organic molecules, brought by comets to the Earth's surface, might have had in the development of life.

2. Comet composition

2.1. Ground-based spectroscopy

Astronomers have been collecting optical spectra of comets since the very beginning of astronomical spectroscopy. In the optical wavelength bands, comets have prominent emissions from C_2, C_3, and CN radicals that are excited by sunlight via resonance fluorescence. The reactive nature of the radical species observed in optical spectra led to the conclusion that these molecules were not primary consituents of the cometary ices. Rather, each is a daughter product resulting from photodisociation of a larger, parent, molecular species.

Prior to the development of instrumentation for observations in the infrared and millimeter-wave portions of the spectrum, comet composition studies relied on piecing together the daughter fragments and speculating about underlying parent molecules. However, beginning in the 1980's and triggered by the strong interest in Halley's Comet, new techniques were tried with some success. The first direct observation of H_2O was made in the infrared (Mumma et al. 1986) The first definitive measurement of HCN was also obtained at millimeter wavelengths (Schloerb et al. 1986; Despois et al. 1986). Since these initial steps, spectroscopic studies in these wavelength regions have become routine with abundances of over thirty species measured relative to water ice, the main volatile constituent of the nucleus.

2.2. Comet orbits and composition

Cometary nucleii were originally formed in the Solar Neubla, a disk of gas and dust surrounding the proto-Sun. It would be highly useful to be able to link the comets that we observe today to an original location within that disk. One possibility is through the possible correlation of a comet's present orbit with its original position in the Solar Nebula.

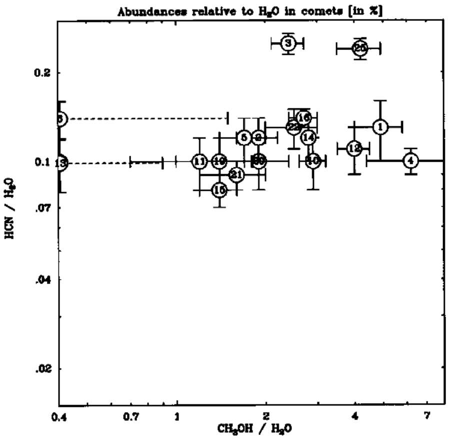

Fig. 2. Abundance of HCN and CH_3OH relative to H_2O in a number of comets. CH_3OH is quite variable from comet to comet, whereas HCN is not. Figure from Biver et al. (2002)

Comets are usually classified according to their orbital characteristics. The *Periodic* comets are those with established orbits. We may further divide these into *Short Period* comets, with periods less than 200 years, and *Long Period* comets with longer periods. Within the group of short period comets, we identify comets of the *Jupiter Family* with periods less than 20 years. These objects have evolved into their present orbits by virtue of gravitational perturbations of comets originating from the plane of the solar system beyond the orbit of Neptune.

The other major class of comets are the *Oort Cloud* comets. This set of objects arrives in the inner solar system on nearly parabolic orbits with random inclinations to the plane of the ecliptic. The present source region is a spherical cloud of comets at distances of 10,000 - 50,000 AU. The Oort Cloud originated from the gravitational perturbations of comets formed inside of the orbit of Neptune.

Measurements of composition in a number of comets, sampling from both of these populations, have been undertaken. This work has been summarized in a review by Mumma & Charnley (2011). Figure 1 shows abundance measurements for six commonly observed specied from many comets. Comets

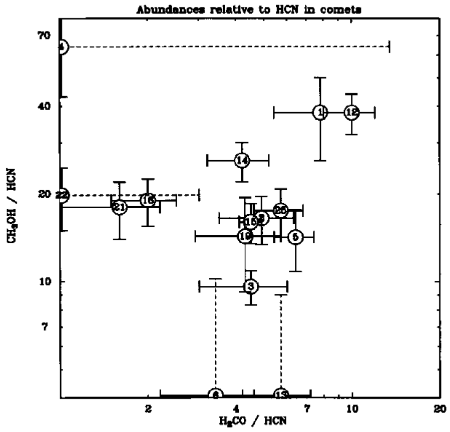

Fig. 3. Comparison of the abundance of CH_3OH and H_2CO with respect to the HCN abundance in several comets. HCN is chosen for normalization since measurements of its abundance with respect to H_2O (see Figure 2) do not show strong variations. CH_3OH and H_2CO are quite variable from comet to comet. The figure shows a possible correlation between the two species, which will have to be confirmed with additional observations. Figure from Biver et al. (2002)

from the Oort Cloud (labeled NI in the figure) and from the Jupiter Family (labeled JF) are highlighted with different colors. No prominent trends have yet emerged, but what does emerge is a large apparent variation in the composition of comets. It is clear that some species (for example: H_2CO, CH_3OH) vary by over a factor of 10, while others, like HCN, are more consistent in their abundance from comet to comet.

2.3. Compositional variations

Biver et al. (2002) presented relative abundance measurments derived from millimeter-wave observations of a number of cometary species. Figure 2 illustrates the relatively large variation in the CH_3OH abundance compared to the HCN abundance. Figure 3 shows a possible trend of the abundance of two species which vary quite a lot from one comet to the next: CH_3OH and H_2CO. The trend is generally in the sense of a positive correlation between these species, though there is clearly a

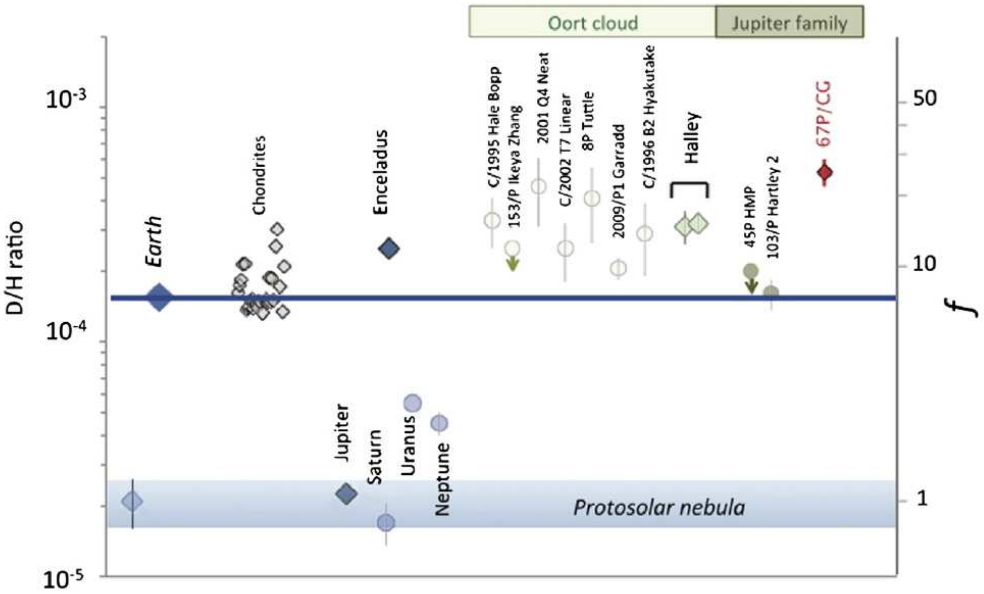

Fig. 4. The measurement of D/H in Comet 67P/Churyumov-Gerasimeko measured with the ROSINA instrument (red point) is put into the context of other D/H measurements of solar system objects. The D/H ratio for Earth is represented by the upper blue line. Comet measurements from both Oort Cloud comets and Jupter Family comets are generally enhanced in D/H compared to the Earth. Figure from Altwegg et al. (2015).

need for additional data to establish that definitively.

3. Lessons from Rosetta Mission

The *Rosetta* Mission to comet 67P/Churyumov-Gerasimenko, carried out by the European Space Agency, has been extremely important to cometary science and has provided many important lessons to inform ground based observations of comets. For measurements of the composition, one of the most important instruments was the high resolution mass spectrometer ROSINA (Balsiger et al. 2007). This instrument detected many ten's of molecular species, including complex organic molecules and noble gasses. ROSINA measurements resulted in the first detection of the simple amino acid glycine in a comet (Altwegg et al. 2016) as well as precise measurements of N_2 (Rubin et al. 2015) and Ar (Balsiger et al. 2015) .

Precise abundance measurements of molecular species relative to water confirmed that there is significant variation in composition from comet to comet. An important example is the measurement of HDO compared to H_2O. ROSINA measurements of 67P/Churyumov-Gerasimnko were found to be consistent with a range of values observed in comets of the Jupiter Family and from the Oort Cloud (Altwegg et al. 2015). Figure 4 shows that the D/H ratio of the Earth's oceans are not consistent with the range of values observed, indicating that comet volatiles may not have been an important contributor to the Earth's oceans and atmopshere, although *some* comets have been observed to have similar ratios. The high abundance of Ar relative to water in the nucleus, about 100 times that observed on Earth, is also consistent with this conclusion.

Another notable result of the *Rosetta* Mission has been a powerful demonstration of

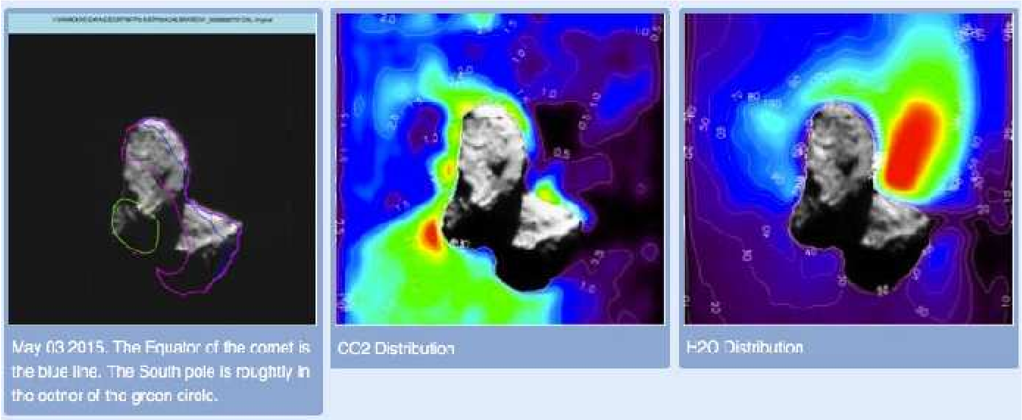

Fig. 5. Images of the CO_2 (center) and H_2O (right) infrared emission from Comet 67P/Churyumov-Gerasimenko obtained by the VIRTIS instrument on the *Rosetta* Orbiter. The two molecular species have very different distributions in the coma since they are produced from different regions on the comet's surface. Figure from Fink et al. (2016).

the complexity of the outgassing from volatile ices in the nucleus. For example, Figure 5 shows pre-perihelion measurements of infrared observations of the distribution of H_2O and CO_2 (Fink et al. 2016). The H_2O gas is seen to originate from the northern hemisphere of the comet nucleus, while the CO_2 dominated gasses appear above the southern hemisphere . This pattern was also observed in measurements of the composition of the gas by ROSINA which found that some species, such as O_2, were found to be correlated with H_2O while others followed CO_2 more closely. Monitoring of the production of H_2O, CH_3OH, NH_3, and CO by the MIRO instrument (Biver et al. 2019), shown in Figure 6, demonstrated that the different species did not follow the same pattern of outgassing through the entire orbit, with, for example, CH_3OH following the production of CO_2 more closely than H_2O.

Taken together, the *Rosetta* results set an important challenge before ground based observers try to understand the composition of comets. As noted from previous ground based work, there is significant variation in the composition of the cometary ices. There are even important differences within groups of comets, as indicated by the differences in D/H among the few Jupiter Family comets that have been measured. It is important to observe a good sample of comets to begin to characterize the differences as a step to understanding their origins.

For the ground based observer we also have the lesson that, in addition to comet-to-comet differences, we have important compositional differences over the surface of a single comet. Thus, a single measurement of the bulk outgassing of a particular species integrated over the entire surface at some point in time during a comet's apparition may not tell the whole story. Indeed it may be difficult to sort out compositional variations reflecting primordial compositional differences between comets from variations over a single comet's surface.

4. Studies of comet composition with the LMT

4.1. LMT capabilities

The LMT is a 50m-diameter millimeter-wave radio telescope, equipped with spectroscopic instruments covering the 3mm, 2mm, and 1.3mm atmospheric windows. Of these, the intensity of millimeter-wave lines strongly favors observations in the 1.3mm window.

As a single dish antenna, the LMT is limited in its angular resolution by the beam size, which is related to the wavelength and diam-

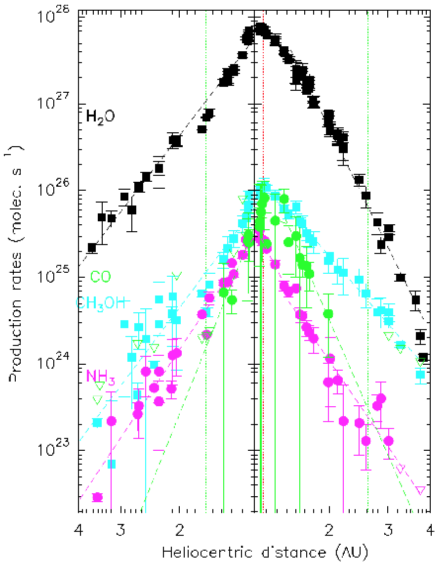

Fig. 6. Results of monitoring the cometary volatiles H_2O, CO, CH_3OH, and NH_3 in Comet 67P/Churyumov-Gerasimenko with the Microwave Instrument for the Rosetta Orbiter (MIRO). The gas production curves show the increase in production as the comet moves to perihelion. The curves are asymmetric about perihelopn due to seasonal effects of the sunlight responsible for heating the ices of the comet nucleus. Figure from Biver et al. (2019).

eter of the primary surface. For the LMT in the 3mm window, this sets the beam to be approximatley 15 arcsec in diameter. For the 1.3mm window, however, the beam is smaller at 6 arcsec in diameter. Molecular line emission from comets is strongly centrally peaked on the position of the nucleus. Sensitivity to comet emission favors large telescopes and small beams, which is one strength of the LMT. Another strength of large single-dish telescopes is the excellent sensitivity to low surface brightness emissions, which permits sensitive mapping observations of the extended coma of the comet.

Exploration of an individual comet by spacecraft, as with the *Rosetta* Mission, is highly rewarding but highly expensive. Moreover, since there is a lot of variability from comet-to-comet, it may be difficult to put the results for any one comet into a proper context. Thus, ground based observations will continue to play a role, and one of the most important objectives will be measurements of relative abundances from comet to comet. A plan for LMT is to embark on a survey of observations that will allow these variations to be characterized. The large size of the LMT ensures that a large sample of objects can be observed, even in comets of only moderate brightness. These characteristics also provide an advantage in searches for low abundance molecules in bright comets.

4.2. Millimeter-wave observables in comets

Measurements of millimeter-wave spectral lines may be used to estimate the *production rate* of molecules from the comet nucleus. Comparison of the production rate for each new species is then compared to estimates of the production rate of water to derive relative abundances. In addition to abundance, the shapes of the spectral lines contain important information. The width of comet lines is related to the outflow velocity of the gas in the coma. The shape of the line provides information about the distribution of outgassing from the surface of the nucleus, since molecules ejected from the side of the nucleus towards the observer are blueshifted, whereas molecules from the side away fro the observer are redshifted by the motion of gas in the coma.

Figure 7 illustrates an important effect on the line shape that occurs when the beam of the antenna resolves the comet's coma. The line shape for an unresolved, isotropic outflow is rectangular, but when the coma is resolved, the beam preferentially sees molecules moving toward or away from the observer. This results in a depletion of the signal near line center and the resulting line has two "horns" at the extremes of velocity. If the flow of gas from the nucleus is *not* isotropic, then the shape of the line will be further affected. For example, if the gas comes primarily from the side of the nucleus facing the observer, then there will be a strong peak on the blue shifted (negative velocity) side of the line, whereas the redshifted

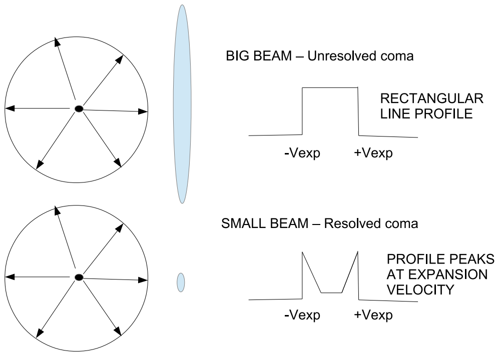

Fig. 7. Cartoon to illustrate the effect that resolution of the coma by the antenna beam has on the comet's line shape. For an isotropic outflow of gas at a single velocity that is *unresolved* by the beam, one expects a rectangular line profile. However, when the comet's coma is *resolved* by the antenna beam, then molecules moving perpendicular to the line of sight are down weighted compared to those move towards or away from the observer. In this case, the result is a decrease at the center of the line and the appearance of two "horns" of emission at the edges of the line profile.

emission (positive velocity) will be reduced yielding a line shape that is asymmetric.

4.3. Comet 46P/Wirtanen observations

To illustrate the potential of the LMT, we summarize some recent results from the December 2018 close approach of comet 46P/Wirtanen made with the LMT's 1.3mm receiver. The comet was observed at a distance of only 0.076 AU, and the 6 arcsec beam of the LMT allowed a linear resolution of only 332 km at the comet. Observations were made during commissioning of the receiver.

Figure 8 shows the result of a five-minute integration on the HCN J=3-2 transition. The line is easily detected by the LMT and shows a strong asymmetric line shape which is indicative of aymmetric outgassing from the nucleus. The production rate of gas was estimated to be 6×10^{24} molecules per second, which corresponds to approximately 0.08% of the water production rate and half of the CN production rate estimated at the time (Schleicher private

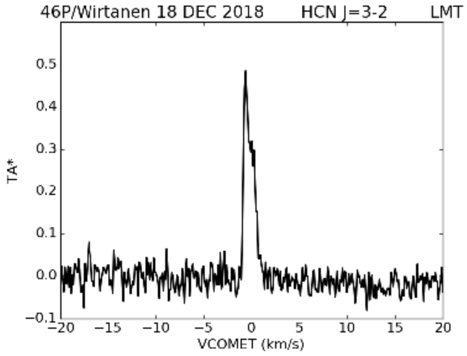

Fig. 8. The HCN J=3-2 transition observed in Comet 46P/Wirtanen at the LMT during December 2018. The line is asymmetric with a stronger peak on the blue-shifted side of the line profile.

communication). The line shape is well fit with an outflow velocity of 700 meters per second. The blue-shifted side of the line is enhanced relative to the redshifted side. For the observation geometry at the time, this would indicate greater outgassing from the nucleus on its day side.

Figure 9 shows one of several CH_3OH spectral lines detected during an integration of about one hour. The line shape is consistent

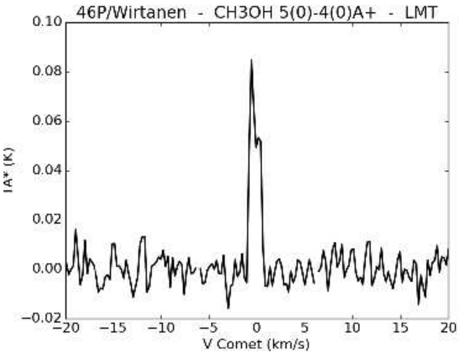

Fig. 9. The CH_3OH $5_0 - 4_0A^+$ transition in Comet 46P/Wirtanen observed at the LMT in December 2018. The line shape is asymmetric with a strong peak on the blueshifted side of the line. The asymmetry is the same as that found for the HCN J=3-2 line shown in Figure 8
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with the same outflow speed and outgassing pattern seen in the HCN (Figure 8). The production rate for CH_3OH is estimated to be 7×10^{25} molecules per second, about 1.2% of water (Schleicher private communication). This leads to a relative abundance of about 14 for CH_3OH relative to HCN. Comparison of these results to those obtained in other comets (Figure 2) shows that this is a rather nominal value.

5. Conclusion

The Large Millimeter Telescope *Alfonso Serrano* has a great potential to make sensitive observations of molecules in the comae of comets. Correlation of abundance variations of commonly observed molecular species from comet to comet with orbital characteristics provide a potential means to address compositional difference within the Solar Nebula. The LMT's sensitivity will enable searches for new, low abundance, species in bright comets that come along in the future.

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