Astrochemistry of Inter- and Circumstellar Matter

Application Note

Introduction

More than 150 different molecules have been identified in star-forming regions. These range from simple diatomic species such as CO to complex organic molecules like CH_3HCH_2CN and exotic carbon chain radicals of which $HC_{11}N$ is the largest molecule observed in inter- and circumstellar matter (ICSM). With exception of H_2, the first astrochemical models explained the formation of molecules entirely by gas phase processes driven by cosmic-ray ionization. Indeed, gas phase models reproduce the observed abundances of the smaller molecules, but they largely fail to explain the presence of more complex systems. Such species are found in 'hot cores' in star forming regions, i.e. in the compact warm and dense gas directly associated with protostars.

In recent years exciting new evidence has been found that surface processes on grains and in ices play a prominent role in the chemical evolution of the ICSM. Icy dust grains act as catalytic sites for molecule formation. The ice mantles are formed either by accretive recombination of more simple species or by 'freeze out' of complete molecules from the gas phase. The latter process occurs during the first stage of star formation and at this stage surface catalyzed processes take place. Later on in the star formation sequence, the grains are warmed to temperatures where molecules desorb again.

Detailed laboratory studies in which interstellar ice analogues are formed and surface reactions are initiated by UV irradiation (or similarly important via atom-bombardment) are currently a hot topic in astrochemistry. It is possible nowadays to grow interstellar ice analogues with monolayer precision and atom-collision or photon-induced processes can be studied temperature dependent with infrared spectroscopic or mass spectrometric techniques.

The commercial availability of highly sensitive frequency selective optical detectors allows an extension of this research to ultraviolet and visible wavelengths, a frequency domain where astronomical observations have been historically very strong. For this it is important that larger frequency domains can be scanned fast and sensitive with a resolution that is acceptable for spectral features in the solid state. An increase in sensitivity can be achieved by using a multi-pass configuration in which a sample is mounted inside an optical cavity. In the last years much progress has been made in the laboratory using cavity enhanced technologies, most noticeably cavity ring down spectroscopy, but also incoherent and broadband applications are currently considered as powerful spectroscopic alternatives.

Experimental Set-Up

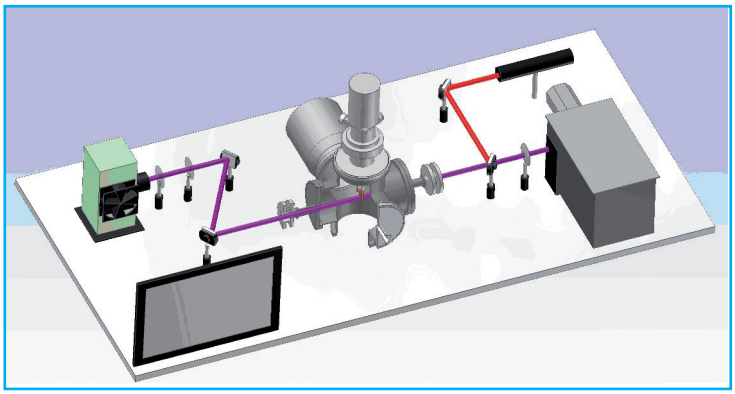

Figure 1: Schematic of the IBBCEAS setup employing a LOT Oriel Xe-Arc lamp and an Andor Shamrock 303i spectrograph with an Andor iDus DV420A-OE CCD detector.

In IBBCEAS (incoherent broadband cavity enhanced absorption spectroscopy) the light of a Xe-Arc lamp (e.g. LOT Oriel 300 W Xe-Arc lamp) is focused into a stable optical cavity that consists of two highly reflective mirrors. The reflectivity of these mirrors is better than 99.5%. A set of lenses images the brightest zone of the arc lamp through the cavity. The two mirrors are mounted to a vessel, in which inter- and circumstellar ice analogues are grown on a substrate that is cooled down to temperatures as low as 10 K by a closed He-cryostat. The substrate is positioned in such a way that the light of the arc lamp passes through in transmission. The light that is transmitted by the cavity is coupled onto the entrance slit of the automatically calibrated grating spectrometer, resulting in a typical spectral resolution of the order of 0.05 nm.

The principle of IBBCEAS is very close to that of other cavity enhanced techniques: light is confined to a cavity with a high finesse but instead of using a narrowband laser source with subsequent determination of individual ring down events, broadband radiation is applied and the cavity is used as a high quality multipass system. Frequency dependent information is obtained by resolving the light that leaves the cavity into its spectral components by a spectrometer. Assuming only losses due to the limited mirror reflectivity (R),

the light intensity is inherently reduced by a factor of 0.5 (1-R) by the resonator and further lowered by the spectral transmission of the spectrometer. Therefore, a cooled 1024 x 255 pixel CCD array detector with low noise level (e.g. the iDus DV420A-OE) has to be used. In combination with sophisticated software and by integrating and averaging transmitted light the optical (i.e. electronic) properties of inter- and circumstellar ice analogues can be studied. The same is true for chemical reactions in the ice.

First Results

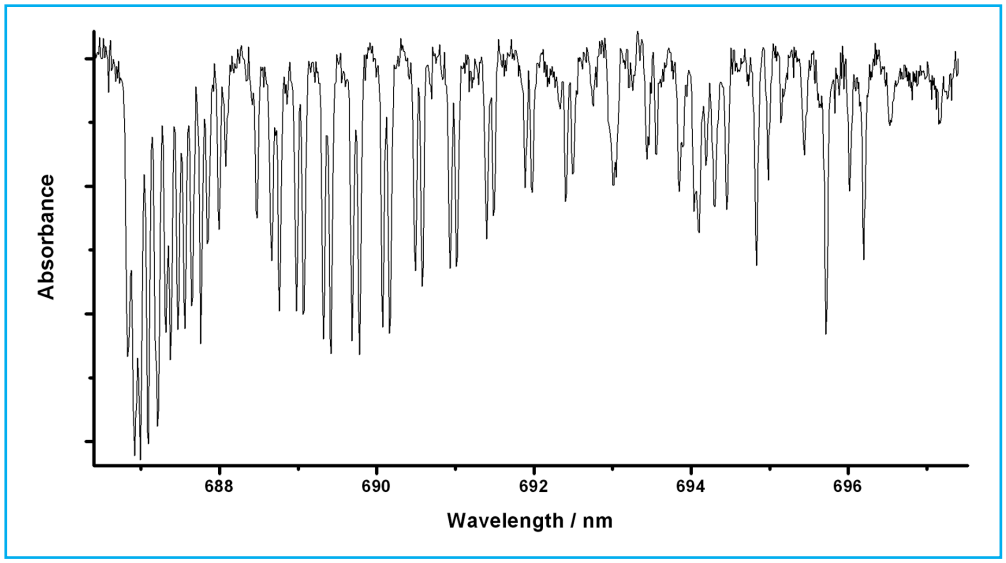

Figure 2: A typical absorption spectrum of the doubly forbidden $b^1\Sigma_g^+$-$X^3\Sigma_g^-$ (1,0) molecular oxygen transition measured with the IBBCEAS setup of figure 1.

Currently data have been obtained for such ices, but as these have not been published yet, the operation of the new setup is demonstrated on the example of the $b^1\Sigma_g^+$-$X^3\Sigma_g^-$ (1,0) electronic transition of molecular oxygen around 688.4 nm. One should realize that this transition is highly (spin and parity) forbidden, nevertheless it is possible to record a 20 nm broad spectrum in less than a few minutes using the technique of IBBCEAS as demonstrated above.

Clearly, IBBCEAS is going to improve optical detection techniques in the UV/VIS/NIR. It is particularly the rather straight forward application – based upon direct absorption spectroscopy – that shows the potential of this technique.

We hope to be able to present soon the first optical ice spectra as well as the reaction kinetics in inter- and circumstellar ice analogues that will guide future observations and that are needed as input in astrochemical models.

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