Microwave Molecular Spectroscopy with the Arecibo Telescope

The Arecibo Upgrade of the late 1990's opened up the full 1-10 GHz frequency range to observers. A major goal in making this wide expanse of spectrum available to Arecibo users was to greatly enhance the appeal of the Observatory for molecular-line observers. Indeed, recent Galactic and extragalactic observations at Arecibo have demonstrated the power of using the great sensitivity of the 305-m dish to detect molecular species that would otherwise require prohibitively long integration times to achieve the same sensitivity with other single-dish telescopes.

In this document, the success of Arecibo molecular-line observations over the past decade, and the promise for the future will be highlighted. To this end, we will close with a brief description of instrumental developments that would enhance even further Arecibo's potential to contribute to this fundamental field of Galactic and extragalactic radio astronomy.

Molecular Studies of Our Own Galaxy

While the ground-state transitions of the OH molecule were observable at Arecibo pre-Upgrade, the high-sensitivity 1-10 GHz receiver systems have provided much enhanced power for observing both ground- and excited-state transitions of this important molecule within our Milky Way Galaxy. Studies of OH (and CH) in molecular clouds (including high-latitude translucent clouds) illustrate the potential of the telescope to contribute to cutting edge studies of the interstellar medium (ISM). As OH can be easily observed in low density interstellar clouds, its value is well illustrated by the present "hot topic" of the existence of "Dark Molecular Gas" (DMG). While H_2 molecules are usually traced via associated CO emission, both EGRET gamma-ray observations, and infra-red observations of cold dust provide evidence for considerable low-density H_2 gas that does not have significant amounts of associated CO emission. However, at lower densities than those at which CO is dissociated, OH is expected to be a good tracer of H_2. Thus, wide-area, λ18-cm OH mapping at Arecibo should be able to resolve the situation, and will likely trace out this previously unrecognized component of the ISM.

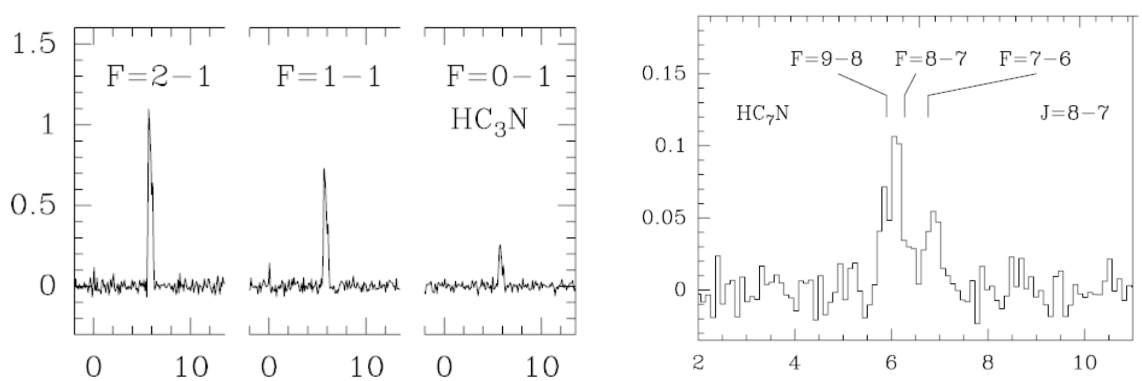

Fig1: Spectra in TMC-1 of (**Left**) the J = 1-0 transitions of HC_3N and (**Right**) HC_7N. The horizontal axes are the LSR velocity in km/s, while the vertical axes are the antenna temperature in K. (Kalenskii *et al.* 2004)

Immediately post-upgrade, making spectral scans on hot cores in "massive star"-forming regions such as W51e2, or dark clouds such as TMC-1, was limited by the power of available spectrometers. This was especially true for dark clouds, where a velocity resolution of 0.1 km/s is required given the expected line widths. Nevertheless, indications of the potential of the telescope was provided by Kalenskii *et al.* (2004; Fig. 1). The situation is much improved today with the availability of the "single-pixel mode" of the Mock spectrometer. A full 1-10 GHz spectral survey of W51IRS1 was recently completed, while exploratory scans on W51e2 have detected CH_3OH transitions up to 10058 MHz. In respect of hot cores, Arecibo can help by detecting multiple transitions of a given molecule at very different frequencies, allowing determination of the excitation conditions. As well as hot cores in “massive star”-forming regions, attention should be paid to “hot corinos”, presumed to be similar to hot cores, but surrounding low-mass protostars.

In very cold clouds, such as TMC1 (T~10 K), large complex molecules emit mainly lines of low-energy transitions that can only be observed at microwave frequencies. This allows Arecibo to have importance in studying the chemical evolution of cores in such regions. Arecibo can also provide deeper 1-10 GHz spectral surveys of evolved stars, such as IRC+10216. Of course, the above studies would all benefit greatly from a 1-10 GHz wide-band receiver and an appropriate spectrometer (see below).

In addition, Arecibo has provided “molecular surprises” within our Galaxy. For example, Araya *et al.* (2010) have shown that the rare H_2CO maser in the young massive stellar object, IRAS 18566+0408, displays quasi-periodic flares that are closely correlated with similar variability of the object's CH_3OH masers (Fig. 2).

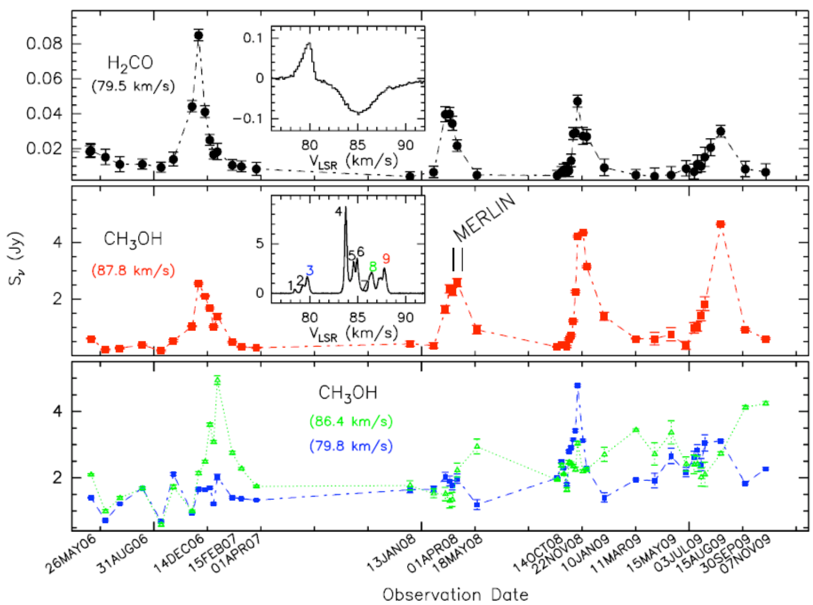

Fig 2: Spectra of the H_2CO and CH_3OH masers in IRAS 18566+0408 obtained with the Arecibo Telescope on 2006 December 14 (**insets**). The Arecibo light curves from 2006 May to 2009 November of the H_2CO (**top panel**) and of three CH_3OH maser components (**middle and bottom panels**). The H_2CO absorption at 85 km/s originates from the extended molecular cloud where the massive (proto)star is located.

Extragalactic Molecular Studies

While the OH molecule was observable at Arecibo pre-Upgrade, the broad frequency coverage of the L-Band Wide receiver system provides much greater power for the discovery of new OH absorbers and megamaser emitters in external galaxies. The extensive survey for such objects by Darling & Giovanelli (2002; Fig. 3) discovered 50 new OH megamasers (OHMs) in (ultra)luminous infrared galaxies (ULIRGs), doubling the known sample of OHMs, and increasing the sample at $z > 0.1$ sevenfold.

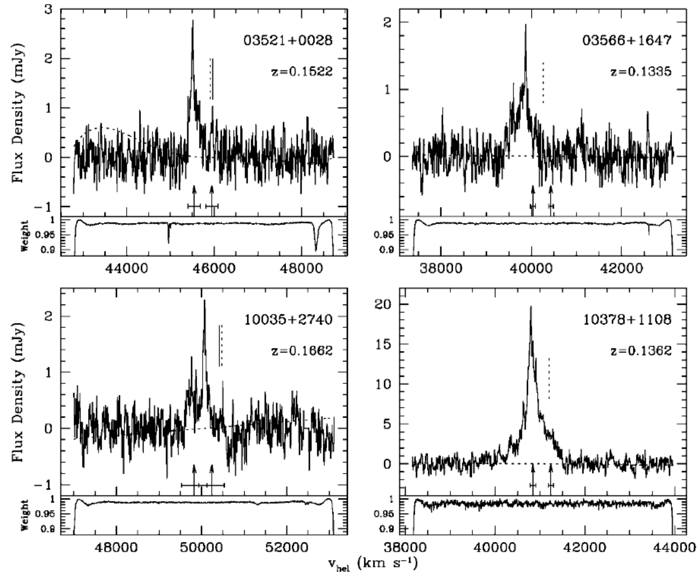

Fig. 3: Four of the OH megamasers discovered in (U)LIRGs by Darling & Giovanelli (2002). Abscissae represent the optical heliocentric velocity for the 1667.36 MHz line. Arrows indicate the expected velocity of the 1667.36 (left) and 1665.40 (right) MHz lines, with error bars indicating the redshift uncertainty. The dashed vertical lines indicate the expected position of the 1665 MHz line, based on the centroid of the 1667 MHz line; a match between the two indicates a possible detection of the 1665 MHz line. The dotted baselines indicate the shape (but not the absolute magnitude) of the baselines subtracted from the calibrated spectra. The small frame below each spectrum shows the "weights" spectrum, indicating the fractional number of RFI-free records averaged in each channel.

An example of a full extragalactic line search at Arecibo was the pathfinder Arp 220 spectral scan that made the first detection of the pre-biotic molecule Methanamine (CH_2NH) outside of the Local Group (Salter *et al*. 2008; Fig 4). It also detected four bending transitions of HCN that had never before been observed, found a number of transitions of excited OH that were not previously known in this Ultra Luminous Infra-Red Galaxy (ULIRG), and revealed a likely absorption feature, since confirmed, from Methanol (CH_3OH), again a first detection of this molecule beyond the Local Group. All these, plus many other new detections, have been confirmed by a follow-up survey of the same ULIRG, that achieves twice the sensitivity. Since 2007, a number of additional projects have made wide-band spectral scans of other (U)LIRGs covering several GHz of bandwidth. The provision of a wide-band 1-10 GHz receiver, and a very broad-band, high-resolution backend (see below) would allow such studies to acquire at least an order of magnitude more integration time at each frequency for the same telscope allocation!

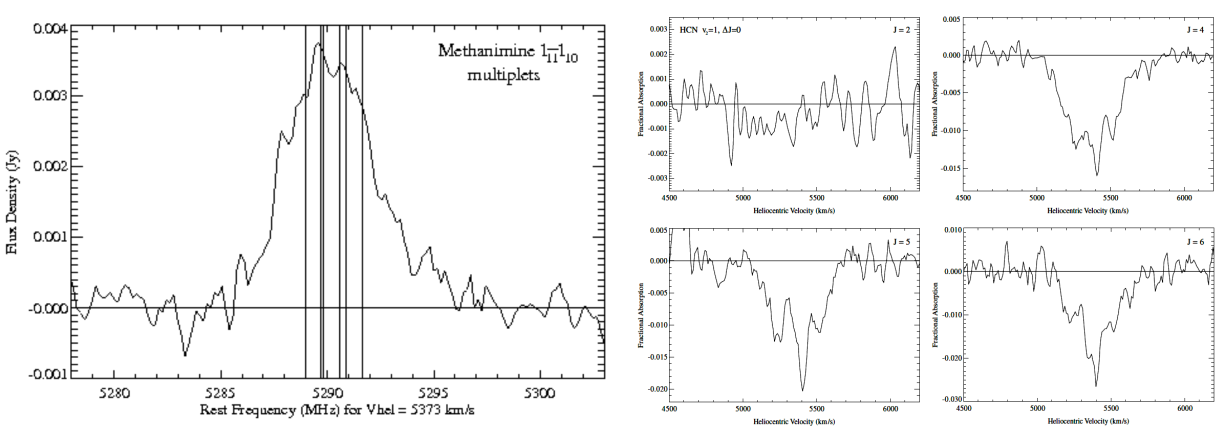

Fig 4: Left: The blended emission line from the $1_{10}-1_{11}$ multiplet of CH_2NH in Arp 220. The rest frequencies of the six individual transitions are shown by vertical lines for an assumed heliocentric velocity of 5373 km/s. The velocity resolution is ~30 km/s. **Right:** The first astronomical detections of the v_2=1 direct l-type absorption lines of HCN with vibrational levels J = 4, 5 and 6 (at 4488, 6731 and 9423 MHz respectively). The spectra are plotted with heliocentric velocity as abscissa. The non-detection of the J = 2 vibrational level (at 1346 MHz) is also included in the figure. The velocity resolution is ~30 km/s. (Salter *et al*. 2008)

Heiles et al. have used Arecibo to measure line-of-sight magnetic fields of 1-10 mGauss from the Zeeman splitting of OH megamaser emission in a sample of ULIRGs. This has been followed up with HSA (including Arecibo) VLBI imaging of the Stokes-V component to trace the magnetic field distribution in these objects, shedding light on the fueling of ULIRGS containing central AGNs.

Radio molecular spectroscopy plays a major role in probing secular changes in the fundamental constants of nature through precise frequency calibration and high spectral resolution. Until the advent of the SKA, Arecibo has a special role to play here. Deep Arecibo integrations on the conjugate satellite OH lines for the z = 0.247 absorber towards PKS 1413+135 has already set useful limits on secular changes in the fine structure constant, the electron/proton mass ratio, and the proton gyromagnetic ratio (Kanekar, Chengalur & Ghosh 2010). These values can be improved as suitable new OH targets are found.

Arecibo searches have been made on samples of high-redshift radio sources for 22-GHz H_2O maser emission. While these have not yet resulted in detections, Bennert *et al.* (2009) detected such a maser at z = 0.66 in the part of their sample observed at Green Bank. Further, an H_2O maser found at Effelsberg in the lensed quasar MGJ0414+0534 at z = 2.64 was followed up through a monitoring program made possible by the high sensitivity of Arecibo (Castangia *et al*. 2011). Clearly, the detection of 22-GHz H_20 masers (and possibly the 22-25 GHz absorbers and emitters of NH_3) in high-z objects is a topic that we have not yet heard the last of.

Again, Arecibo extragalactic molecular observations have provided surprises. In 2008, routine C-band molecular observations detected the appearance of a spectral-line and continuum outburst in the nearby peculiar galaxy, NGC 660 (Fig. 5). The new continuum component has a GHz-Peaked Spectrum (GPS), reaching a peak flux density of ~0.5 mJy at 5 GHz by 2012.0. This has been mimicked by the parallel development of excited-OH maser emission/absorption in its 4660, 4750 and 4765 MHz transitions. H_2CO absorption is also detected against the new continuum source. Follow-up line and continuum VLBI with the HSA (including Arecibo) reveals that we are seeing an outburst in the nucleus of NGC 660.

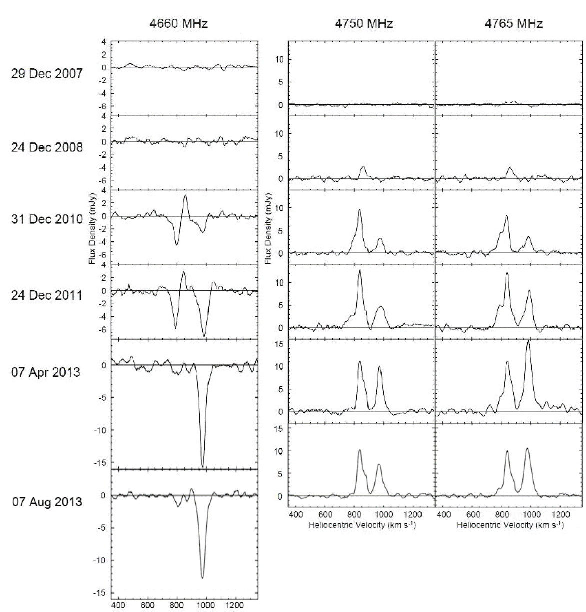

Fig 5: Excited-OH spectra of NGC 660 from December 2007 to August 2013. The columns (left to right) show the 4660, 4750 and 4765 MHz OH lines respectively, while the epoch increases from top to bottom.

Future Developments that could Enhance Arecibo's Potential for Molecular-Line Studies

Apart from the Arecibo Telescope's potential (as presently instrumented) for enabling molecular line discoveries, the following possible developments would each produce a "great leap forward" in that potential. These are;

(a) the provision of a low-noise, wide-band, 1-10 GHz receiver, together with an accompanying ultra broad-band spectrometer would exploit the full potential of the telescope. This would permit extremely deep spectral scans, for example of samples of Galactic hot cores or of (U)LIRGS.

(b) the development of focal-plane arrays designed to exploit specific molecular opportunities. Examples could the λ18-cm OH transitions, the λ6-cm formaldehyde (H_2CO) transitions at 4829 MHz (and other nearby molecular transitions), and the λ4.5-cm maser transition of methanol (CH_3OH) at 6668 MHz. Compared with single-pixel receivers, these allow the coverage of an extended celestial area to a given sensitivity in a much reduced observing time. Clearly a focal-plane array for OH would facilitate the timely investigation of the existence of DMG. H_2CO is a special case as its absorption spectrum against the Cosmic Microwave Background is ubiquitous. A λ4.5-cm wavelength array centered on the well-known 6668-MHz methanol maser line would permit similar surveys for this molecule to the 18.2 sq deg study of Pandian *et al*. (2007), but one going either much deeper, or covering a much wider area. The Pandian et al. survey detected 86 methanol maser sources, 48 of which were new detections. A good example where array receivers could facilitate exciting science would be the wide-area imaging of molecular species in "massive star"-forming regions such as W49 and W51.

(c) Together with other astronomical fields that would benefit from such a development, (e.g. VLBI, pulsar observing, continuum studies, and potentially solar-system radar investigations), molecular astronomy would benefit greatly should the highest usable frequency of the Arecibo telescope be raised significantly. Were the telescope to possess reasonable sensitivity near 25 GHz, then studies of the important molecular species of H_2O and NH_3 in both the Milky Way and nearby external galaxies would become possible.

References

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