ENCANTO: Research Projects

Research projects we offer as part of the ENCANTO program are briefly described below.

1.0 Multi Messenger Astronomy: VLBI studies of Dual Active Galactic Nuclei

Mentors: Sravani Vaddi, AO, Carmen Pandoja, UPR-RP, Anish Roshi, AO

Galaxies harbor supermassive black holes at their centers. When galaxies merge, the central black holes come together to form Super Massive Black Hole Binaries (SMBHBs). Initially, the separation between the black holes shrinks from ~kpc to ~pc through dynamical friction. As the separation shrinks to parsec scale, the stars that cross their orbit are ejected, further shrinking their orbit. The in-spiraling continues and at some stage the continuous emission of nanohertz GWs aids in shrinking the orbital separation from centiparsec to milliparsec range.

While the above-described scenario gives a general picture of the SMBHB formation and merging process, there are several unanswered questions. Galaxy mergers are accompanied by a massive inflow of gas to the center of the post-merger galaxy. If sufficient gas remains after the galaxy merger, then it can interact with the SMBHB and, in some cases, evolve to a Dual Active Galactic Nucleus (DAGN). In the earlier stages of the merging process (i.e. when the separation is ~kpc to parsec scale), these DAGNs can be studied using high-angular resolution infrared, optical and X-ray observations. The DAGNs with sub-parsec scale separation can be imaged only using Very Long Baseline Interferometers (VLBI). VLBI imaging and monitoring of DAGN systems are extremely useful to address several key scientific questions including details of the co-evolution of the post-merger galaxies and SMBHB as well as accretion phenomenon in DAGNs. In a few cases, the orbital properties and its evolution could be directly measured; for example 3C66B (). SMBHBs with orbital evolution timescales of weeks-to-decades are the primary targets for gravitational-wave detection experiments like the Pulsar Timing Arrays (PTA; Taylor et al., 2016; Mingarelli et al., 2017). Perhaps the only way to probe the co-evolution of SMBHBs and post-merger systems is by combining VLBI observations and PTA studies of DAGN systems [9].

We have observed a few DAGNs with the European VLBI network (EVN) + the Arecibo 305m telescope with the aim to study the radio emission properties and accretion phenomenon. Further we are involved in monitoring the SMBHB in 3C66B using the EVN at 1.6 GHz. We plan to expand this monitoring program to frequencies above 2.5 GHz using the wideband receiver of the 12m telescope + EVN. These observations will provide valuable information about the orbital evolution of the SMBHB, which will allow us to predict the detectability of the gravitational wave signal by the PTA.

Instrumentation component: The cryogenic receiver system for the 12m telescope will be commissioned early next year. As part of this commissiong work, we will be undertaking VLBI test runs with the EVN. The project will thus provide a unique opportunity for students to participate in VLBI observations with the 12m telescope and understand how the system is tested for readiness for such observations, how correlations are made for these observations and how VLBI imaging is done quasi real-time.

2.0 Characterizing the Habitability of Planets Around Red Dwarf Stars in the Radio Spectrum

Mentors: Abel Mendez, UPR-A, Anish Roshi, AO

Radio emissions from red dwarf stars, such as Proxima Centauri and TRAPPIST-1, are of particular interest due to their potential to support habitable planets around them. These stars produce intense stellar flares and coronal mass ejections with high UV and X-ray fluxes visible in the radio spectrum. Many observatories have observed these broad-spectrum emissions, including the Arecibo Observatory. Another source of radio emissions is the interaction of the stellar wind with the magnetic field of a planet producing aurora emissions. For example, emissions from brown dwarfs have been detected with the 305m telescope at 5 GHz, but such emission from planets might be more challenging to detect and may be limited to lower frequencies (<100 MHz). Planets can also be detected by their spectral emissions. For example, hot gas planets have been detected by their OH emissions. Furthermore, any advanced civilization might emit radio waves from these planets as communication or leakage. NASA is back at looking for technosignatures, including those associated with extraterrestrial communications in the radio spectrum.

The main goal of this project is to characterize the habitability of planets around red dwarf stars from radio emissions. Our objectives are (1) to characterize the space weather of potentially habitable planets around red dwarf stars, (2) to search or confirm planets via planet-star interactions, (3) and to search for technosignatures. We have four years of data from observations of red dwarf stars with planets using the 305m telescope (Project A3123). We will look for broad-band transient or quiescent emission due to flares or coronal mass ejections from the stars, or due to aurora emissions from planets. We will look for emissions or absorption lines from the stars or planets. We will also look for technosignatures from frequency-specific transient or quiescent communications. The detection of transient but intense flaring emissions might indicate unfavorable conditions for the atmosphere of any planet. Non-detections would be used to constrain the upper limits on stellar activity, the presence of additional planets, or the lack of any radio-capable civilization around our observed stellar systems.

Instrumentation component: Identifying man made radio frequency interference (RFI) over 300 MHz to 10 GHz and documenting them will vastly help the project as the signatures we are trying to detect can be in the frequency range outside the allocated band for radio astronomy. As part of the project, the students will get the opportunity to use sophisticated lab instruments and set up RFI measurement systems at AO to measure and identify man made RFI.

3.0 Molecular cloud formation: CH 3.3 GHz Survey of the Galactic Plane

Mentors: Allison Smith, AO, Mayra Lebron, UPR-RP, Anish Roshi, AO

The interplay between gas and stars dictates the evolution of spiral galaxies, both large and small. However, even though molecular clouds represent a fundamental stage of the star-gas cycle, the details of how molecular clouds form and evolve have so far avoided elucidation. In addition, gamma-ray and infrared data indicate that a substantial amount of molecular gas remains undetected by the existing large-scale CO sky maps (Grenier et al., 2005). This gas is now known as 'CO-dark gas,' and many studies have tried to address how much of the Interstellar Medium (ISM) is tied up in this material (e.g., Planck Collaboration XIX, 2011; Donate and Magnani 2017). Therefore, spectroscopic observations of other molecular transitions in the radio regime are critical for detecting this gas, as they provide the velocity information that the gamma-ray and infrared maps can not. The velocity structure of this low-density (< 500 cm^{-3}), extended molecular gas holds the key to unraveling its relationship with the atomic hydrogen medium from which it condensed. This gas is likely to be gravitationally unbound and thus carries the primordial kinematic signature from its formation processes.

Several studies have shown that the CH 3.3 GHz hyperfine, ground state, main lines are capable tracers of CO-dark molecular gas (Magnani and Onello 1993, Liszt and Lucas 1996; Xu and Li 2016), and the use of the 12m telescope at AO to produce a full sky map of the CH emission along the Galactic plane would represent a tremendous step forward with respect to detecting the CO-dark gas and illuminating the physical mechanisms that govern the atomic-molecular transition. In addition, it would simultaneously enable opportunities to resolve or better constrain other questions related to both the ISM as well as early-stage star formation, including the following:

1) Stringent tests on the astrochemical models of molecular clouds: one of the first products in the carbon reaction network, CH is also known to grow linearly with H_2 in the diffuse ISM, and hence is a robust tracer of H_2 (Magnani and Shore 2017). The CH map of the galactic plane can be compared with the full sky CO map produced by Dame et al. (2001) for this test.
2) It has been predicted that MHD waves enhance CH abundance along the boundaries of molecular clouds (Draine & Katz 1986). Comparing the spatial structure of the CH emission detected in the 12m survey with Planck dust polarization emission at 353 GHz (Planck Collaboration XIX 2015) can provide insight into possible enhancements of CH formation by interstellar magnetic fields.
3) Just as the CH 3.3 GHz lines are common tracers of molecular gas in various regimes of the ISM, they may also be useful, unconventional tracers of stellar formation. For example, Sakai et al. (2012) show CH emission is prevalent throughout the Heiles-2 Cloud in the TMC-1 star forming region, and distinctive narrowing and widening of the CH line widths appears to trace different evolutionary stages of the gas.

The 12m CH survey project would thus provide a comprehensive view of giant molecular clouds, and because of the kinematic information, would allow us to study the relationship between different components of the molecular gas and the cold neutral medium of the ISM on a Galactic scale.

Instrumentation component: The CH lines are weak and so we need deep integration to detect these lines. Moreover, man made radio frequency interferences are present near the CH line frequencies. A large scale survey therefore requires software packages that can largely automate the data processing and provide science ready data products. Students, if interested, will get an unique opportunity to get involved in such software development (mostly IDL, python and C++).

4.0 Prebiotic and other Molecules in the Milky Way

Mentors: Allison Smith, AO, Chris Bennett, UCF, Mayra Lebron, UPR-RP, Anish Roshi, AO, Anna McGilvray, AO

The wide frequency coverage of the cryogenic front-end of the 12m telescope is ideal to survey molecular line emission between 2.3 - 14 GHz. A sample of these lines are listed in Table 2. In conjunction with the advantages of having dedicated telescope time assigned to these studies, the frequency coverage constitutes opportunities to investigate the distribution of molecular gas in our galaxy as well as search for prebiotic molecules in these environments. An Arecibo archival data set, which provides a more sensitive, targeted search for molecular emission over 1 to 10 GHz toward W51A is also being processed. We discuss below a few of the most interesting cases of molecular line studies.

Table 2: Molecular lines of interest in the 12m telescope frequency range

CH	3.264, 3.336, 3.349 GHz
H_2CO	4.83, 14.48 GHz
HC_3N	9.098, 9.097 GHz
HC_5N	2.662, 5.324, 7.988, 10.65 GHz
HC_7N	5.640, 7.896, 9.024, 10.15, 10.65 GHz
HCOOH	4.9 GHz

The K-doublet transitions of H_2CO at 4.8 and 14.5 GHz can be used effectively as a densitometer to probe the properties of molecular gas (Ginsburg et al. 2011). The H_2CO lines could be observed simultaneously with the galactic CH survey which would provide a unique opportunity to detect H_2CO and perform densitometry over large areas of the galactic plane. Existing CO(1-0) surveys do not distinguish the high density regions from the lower density regions. Thus, combined with H_2CO densitometry studies, these observations would probe inhomogeneities of the galactic plane at a level that has not been possible to date. Cyanoacetylenes (e.g., HC_3N, HC_5N, and HC_7N) are also excellent density tracers (see, e.g., Bergin et al. 1996), and a full galactic plane survey of these molecules would probe the distribution of gas in and around GMCs in the disk of the Milky Way. Formic Acid (HCOOH), an important prebiotic molecule in the interstellar medium, is similar in structure to simple amino acids, plays a role in the formation of glycine, and would be useful to include in a large-scale spectral line survey. It was observed in Sgr B2 with the NRAO 140-ft telescope (Zuckerman et al. 1971), and the 4.9 GHz transition of HCOOH has been observed using the 305m telescope (using the mini-Gregorian; Loris Magnani, private communication).

5.0 Star formation and Diffuse Ionized gas in Cygnus X region

Mentors: Anish Roshi, AO, Mayra Lebron, UPR-RP, Chris Salter, AO

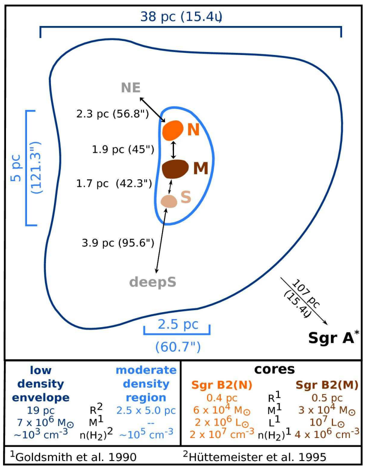
Massive stars produce copious amounts of UV photons, which ionizes the gas in their surroundings. A small fraction of these photons can travel large distances through the interstellar medium (ISM). These photons produce low density (< 10 cm^{-3}), diffuse ionized gas (DIG), which is observed to extend over hundreds of parsec. Hydrogen in the DIG is fully ionized, but in many regions, the helium is only partially ionized. This under-ionization of helium is unexpected, as the most massive stars produce both hydrogen and helium ionizing photons. The

Cygnus X region (d ~ 1.5 kpc) is one of the most massive star forming complexes in our Galaxy. This region represents a ~10º wide region in the galactic plane near galactic longitude l=80º. The region is rich in OB associations, DIG, atomic and molecular gasses. A wealth of observational studies already exist to characterize the different components of ISM as well as OB stars in the Cygnus X region. Recently we have made extensive observations of low frequency (< 900 MHz) radio recombination lines toward Cygnus X region using the Green Bank Telescope (GBT). These lines preferentially originate from the DIG and so form an excellent tracer of low-density ionized gas. We have also made complementary continuum observations of the same region with the 12m telescope at AO near 8.3 GHz. The student will be involved in making a continuum image of the Cygnus X region using the 12m telescope data. The long term aim of the project is to combine GBT, 12m telescope and other data sets to constrain the properties of the DIG and understand the helium ionization issue.

6.0 Cyanoacetylene (HC3N) in Star-Forming Regions

Mentors: Chris Salter, AO, Tapasi Ghosh, Allison Smith, AO, Mayra Lebron, UPR-RP

Sagittarius B2 (SgrB2) is one of the most massive molecular clouds in our Milky Way Galaxy. It lies just over 100 pc from the Galactic center, and some 8.3 kpc from the Sun. It contains three distinct structural components, shown in this cartoon (Schmiedeke et al, 2016, A&A, 588, 143).



There is a low-density envelope of about 40 pc (15 arcmin) diameter, and a moderate-density region of ~2.5 × 5 pc, within which is contained three active massive-star formation sites, N(orth), M(ain) and S(outh), each hosting ultra-compact HII regions. SgrB2 is perhaps the richest source of molecular radio line emission in our Galaxy.

The Arecibo 12-m Telescope

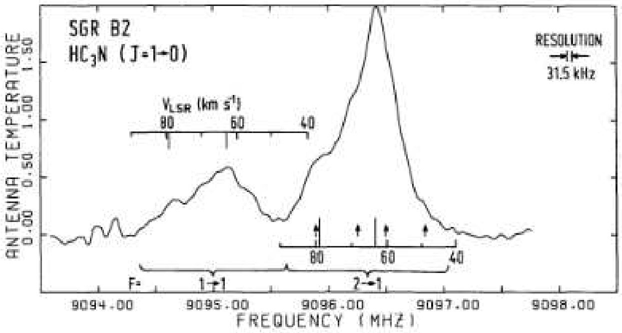
The Arecibo Observatory 12-m is situated atop a hill by the main entrance to the observatory site. At present (Aug 2022) it is available with an X-band (8-10 GHz) receiver system, providing orthogonal circularly-polarized signal channels. The uncooled receiver has a system temperature of about 110 K. The 12-m telescope system has a beam pattern with a Full-Width Half Maximum (FWHM) close to 10 arcmin at 9 GHz.

For spectral-line observations, it records data through the “Mock Spectrometer” with up to 7 independent frequency “chunks”. Each “chunk” can contain up to 8192 frequency channels.

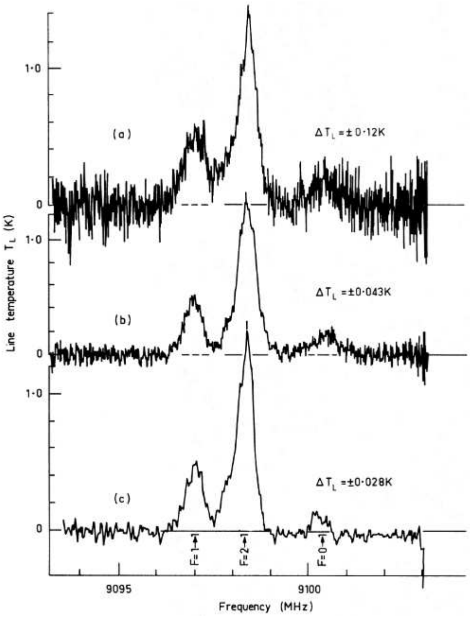
The ENCANTO HC3N Spectral-Line Observing Project

The X-band region of the radio spectrum (8 – 12 GHz) is relatively poor in strong molecular lines from celestial sources. In the “Lovas Catalog”[1], by far the strongest entry is the J=1-0 transition of Cyanoacetylene (HC3N), which is a hyperfine triplet near 9.1 GHz. This was detected with the Parkes 64-m telescope by McGee et al (1975, ApJ, 202, 76), and also by Churchwell et al (1977, A&A, 54, 925) with the Effelsberg 100-m dish. The F=2-1 line was much the strongest of the three hyperfine transitions, followed by the F=1-1 line, with the F=0-1 transition being more than an order of magnitude fainter than the F = 2-1 feature. The rest frequencies of the three hyperfine transitions of HC3N are F=1-1 (9.0970345 GHz), F-2=1 (9.0983319 GHz), and F=0=1 (9.1002725 GHz).

The spectral line of HC3N detected in SgrB2 by Churchwell et al (1977) was;



Earlier, McGee et al (1975) detected the spectral line of this triplet from SgrB2 for three different frequency resolutions, as;



As a “Hands-On Project” for a student group group at the NAIC/NRAO Single-Dish Summer School in May 2022, a successful attempt was made to detect the HC3N molecular line from

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[1] https://physics.nist.gov/cgi-bin/micro/table5/start.pl

SgrB2, (see below), demonstrating that this molecular line can be detected with the present 12-m system.

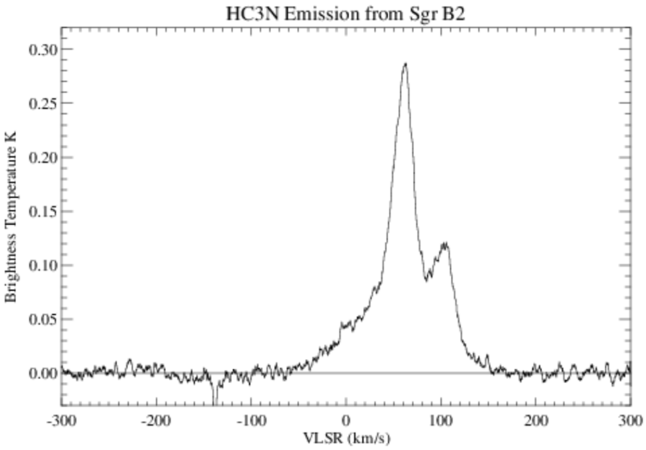
Proposed ENCANTO Project

The spectrum of HC3N taken on Sgr B2 during the Summer School was taken with the present room- temperature receiver. A greatly improved cryogenically-cooled receiver will be installed by the end of 2022. We propose a survey for the presence of the HC3N molecule in a number of high-mass star formation regions within our Milky Way Galaxy. This should permit an interesting astrochemistry study.

Observational Method

The project observations will be performed using a single box ("chunk") of the Mock Spectrometer with a total bandwidth of ~26.7 MHz and 4096 frequency channels. The center frequency of the spectrum will be offset 5 MHz above the rest frequency of the F = 2-1 hyperfine transition to avoid the central spike of the spectrum due to the AC-coupling of the spectrometer. The observations will be made via ON-OFF position switching using a cycle of 5-min ON, 5-min OFF, 10-sec CAL-ON, 10 sec CAL-OFF. Observing close to transit would be optimum.

At the Sinlge Dish Summer School, the HC3N spectral line obtained on Sgr B2 for about 2.6 hours of ON-source integration, with the brightness temperature expressed in K, and the Local-Standard-of-Rest radial velocity given for the F=2-1 hyperfine transition, was;



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7.0 Near-Earth Object physical and dynamical characterization

Mentors: Desiree Cotto, UPR-H, Flaviane Venditti, AO, Sean Marshall, AO, Maxime Devogele, AO

It is widely accepted that the Near-Earth Objects (NEOs) represent a global hazard for human civilization. They have impacted many bodies in the Solar System, including the Earth. More notorious was the Near-Earth asteroid (NEA) with an estimated diameter of 17 meters that exploded over Chelyabinsk in Russia with an energy of about 470 kilotons in 2013 and injured over 1,500 people. Due to the possible devastating consequences of such impacts, Congress assigned NASA the task to detect, track, catalogue, and characterize the physical characteristics of 90 percent of the NEO population down to 140 meters in size. While it is of vital importance and priority to detect these objects, it is also of vital importance to characterize them in order to develop a correct deflection strategy in case of an imminent impact.

Photometry

An asteroid photometry campaign has been initiated with the intent of obtaining lightcurves of NEAs in order to determine their rotation periods. The rotation rate distribution of NEAs can give us important information about their material strength. A 1.0-m Plane Wave telescope of the Navy Precision Optical Interferometer (NPOI) at the Lowell Observatory in Flagstaff, Arizona is used by the University of Puerto Rico at Humacao, as members of the National Undergraduate Research Observatory (NURO) Consortium, to obtain the photometric data of asteroids. Observing runs of 3-6 nights are conducted each semester with 3-4 undergraduate students. Each object is observed using an R-band filter for about four hours on multiple nights. The exposure time is typically 30 seconds and random time delays are inserted in order to avoid problems with aliasing. Additional data is also obtained via ROBO mode on certain nights per semester. The data reduction and analysis of the data is conducted using the Image Reduction and Analysis Facility (IRAF) and the Minor Planet Observer (MPO) Canopus program. The results are published in the Minor Planet Bulletin.

Radar

Arecibo near-Earth asteroids (NEAs) radar observations are used to refine their orbits, which are used to analyze the impact hazards, and to study their near-surface properties. The radar system responds quickly to new NEA discoveries along with the continued survey; therefore, some existing data have not been completely reduced or analyzed. Spectra and images yield sizes, shapes, and spin rates for these objects. The processed continuous wave (CW) and delay-Doppler radar images are used to obtain physical characterization of asteroids. The processed data is used for numerical inverse modeling to create 3-D shapes of near-Earth asteroids using the SHAPE software and can be combined with optical lightcurve data to generate a more complete physical characterization. In addition, the information obtained with the physical characterization can be used to analyze the dynamical environment around NEAs.