ARECIBO REDS: RADIO SPECTROSCOPY OF GLIESE 436. A. H. Colón Cesaní[1,2], G. M. Ferrer Imbert[1,3], K. N. Ortiz Ceballos[1,4], and A. Méndez[1], [1]Planetary Habitability Laboratory, University of Puerto Rico Arecibo, Arecibo, Puerto Rico, 00612 (arianna.colon@upr.edu), [2]University of Puerto Rico - Mayaguez, Mayaguez, Puerto Rico, 00682, [3]University of California Berkeley, Berkeley, California, 94720-2284,[4]Center for Astrophysics | Harvard & Smithsonian, Cambridge, MA, 02138.

Introduction: Red dwarf stars host potentially habitable exoplanets that can provide clues about the conditions that might support life beyond our Solar System [1]. Radio spectroscopy analyses of these stars allow us to determine some factors that might control planet habitability. While prominent spectral lines can be utilized to determine the abundance and temperature of the elements that make up a star, observable spectroscopy patterns can provide information about their composition and magnetic activity [2]. The absence of specific lines can indicate a low abundance of elements that affect the stellar metallicity and the composition of habitable planets. We use observations from the Arecibo Observatory to search for spectral lines from radio emissions of Gliese 436 and other red dwarf stars. This research is a continuation of the Arecibo REDS (A3123) project. We aim to study the stellar environment that could impact or sustain habitable planets in these systems. This research analyzes the patterns, sizes, and widths of spectral lines from over one terabyte of data from various observations. The spectral analyses will allow us to characterize the composition of the red dwarf stars and the space environments around their planets.

Radio Spectroscopy: The Arecibo Observatory can be used to search for astrophysical masers and specific compounds in stellar and space environments [3, 4]. It was a highly successful tool that could determine the presence of essential elements in the stars. Commonly detected spectral lines from emissions in the radio spectrum are those of hydroxyl (OH), Methanol (CH_3OH), and Methyladyne (CH). Hydroxyl, water, and silicon monoxide molecules produce strong masers in M-type stars, such as the ones we have observed from Arecibo [3]. Moreover, oxygen-rich stars are known for being powerful maser emitters [5]. High-resolution spectroscopy is a promising method for characterizing the atmospheres of hot Jupiters and other exoplanets [9]. Radio observations could facilitate the detection of lightning-induced emissions in the atmospheres of planets outside the Solar System [2]. Although the radio telescope at the Arecibo Observatory collapsed in 2020, extensive amounts of data are still available to be studied for crucial and cutting-edge scientific research.

Table 1: Common Stellar Molecular Species

Name	Radio Frequencies
Hydroxyl (OH)	1612.231 MHz
	1665.402 MHz
	1667.359 MHz
	1720.530 MHz
Methanol (CH_3OH)	1728.19000 MHz
	4091.78200 MHz
	4955.20000 MHz
Ammonia (NH_3)	4176.25700 MHz
Formaldehyde (H_2CO)	4829.660 MHz

Visible transitions in developed spectrographs may correspond to specific atoms or molecules that make up a star or its space environment. In addition, the lines' strength could suggest the species' abundance, given that the strength of a transition is correlated with the number of atoms that undergo the transitions under proper conditions [4]. Assigning specific energy levels to the observed transitions provides details about the degree of excitation of the system, which can be used to calculate the environment's temperature and density [4]. On the other hand, wavelength shifts provide clues about the motions of the species relative to Earth, and broadened spectral lines point to collisions between the observed species [4]. Lastly, separations between component lines reflect the local magnetic field's strength [4]. We are searching for significant lines in radio spectroscopy data from the Arecibo Observatory for our research.

Radio spectroscopy analyses of red dwarf stars and their space environments are essential to identify conditions that sustain or diminish the possibility of life in other stellar systems. These analyses also provide information about the atmospheric evolution of planets and stars. A star's basic, elemental compositions and those of its planets are related [8], and chemical composition is the most vital factor for habitability. Radio spectroscopy analyses of red dwarf stars will constrain the percentage of stars of this type that support habitable planetary conditions and provide essential information for developing improved observation technologies.

Goals and Objectives: Most potentially habitable exoplanets are expected to orbit red dwarf stars, the most abundant and long-lasting type of star in our galaxy. They are also favorable for planetary observations due to their small size. Nevertheless, their charged particles and high-energy radiation produced by chromosphere activity could threaten planetary habitability [1]. Our project aims to study the stellar environments that could impact or sustain habitable zones in these star-planet systems. Moreover, our objectives in this analysis are to characterize the chemical compositions of red dwarf stars and their space environments. Space weather phenomena produced by stellar magnetic activity can affect the chemistry and climate of exoplanets [10]. Therefore, red dwarfs have a direct impact on planet habitability, and spectroscopy patterns can reveal details of these events and conditions.

Data Collection: Our data was collected with the 305-meter radio telescope from the Arecibo Observatory between April and May 2017. The telescope is fully equipped with a 5 GHz dual-linear polarization receiving system, and the utilized observational protocols followed those of [6, 7]. During the observation process, the antenna gain and temperature of the system were $\sim$8 K Jy^{-1} and $\sim$30 K, respectively, for all low zenith measurements. The dynamic spectra were recorded at target positions for 1 to 2 hours. In addition, the spectra were sampled at 0.1 s intervals for the four Stokes parameters by seven 172 MHz bandwidth, 8192-channel, FPGA-based Mock spectrometers, set to cover a $\sim$1 GHz band-pass around the center frequency of 4.75 GHz [7]. The Arecibo C-Band receiver has a center frequency of 4.75 GHz with a half-power beam width of 1 arcmin in azimuth and zenith angles, and the Arecibo Mock Spectrometers were employed for the observations [6]. Furthermore, the dual-linear polarization signal was passed to a set of seven field-programmable gate arrays (FPGA) equipped with Fast Fourier Transform (FFT) Mock spectrometers [6].

Current Results: An initial radio spectroscopy analysis of Gliese 436 was performed, examining spectral data for absorption and emission of electromagnetic radiation in close to 200 spectrographs of the red dwarf star. The data were carefully inspected for peaks and observable patterns to compare with the radio spectrum's most commonly detected molecular species, as shown in Table 1. A general-purpose Python script was designed and implemented to facilitate the analysis of Gliese 436, which searched for specific spectral lines and plotted the irradiance as a function of frequency for selected ranges. The script for Gliese 436 is being further developed to improve our spectral analyses. This comprehensive code can analyze spectral data from any system using Arecibo Observatory spectral data.

Our newly processed Arecibo Observatory data shows many spectral lines corresponding to the molecular species shown in Table 1, but most are associated with the stellar background. Furthermore, we found many microflares events from Gliese 436 that could provide more information about the stellar magnetic field and these and other molecular species. The analysis of this data is still in process, and a manuscript is in preparation and expected to be submitted for publication in May 2023.

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