

ARECIBO REDS: THE STELLAR ACTIVITY OF STARS WITH POTENTIALLY HABITABLE PLANETS. K. N. Ortiz-Ceballos^{1,2}, A. Méndez², J. Zuluaga³, R. Heller⁴, D. Alexander⁵, A. Pacini⁶, ¹Department of Physics, University of Puerto Rico Río Piedras Campus, San Juan, PR, USA (kevin.ortiz22@upr.edu), ²Planetary Habitability Laboratory, University of Puerto Rico at Arecibo, Arecibo, PR, USA ³Universidad de Antioquía, Medellín, Colombia ⁴Max Planck Institute for Solar System Research, Göttingen, Germany, ⁵Rice University, Houston, TX, USA ⁶Arecibo Observatory, Arecibo, PR, USA

Introduction: Red dwarf stars are by far the most numerous stars in the galaxy, and their stellar activity is of special interest due to the potential of these stars to support habitable planets around them [1,2]. Planets around these stars could experience tidal locking, strong stellar magnetic fields, strong flares and high UV and X-ray fluxes, all factors that might affect their habitability. Specifically, they may affect the long-term ability to retain water and other astrobiologically relevant volatiles in the atmospheres of any planetary bodies, and may cause atmospheric erosion [3,4,5].

These stellar flares are often associated with detectable radio emissions. Radio emissions from cool dwarfs are strong, but the absolute fluxes are small and impose severe constraints on the sensitivity of the instrument used to observe them. The Arecibo REDS project exploits the suitability of the Arecibo Observatory for obtaining accurate measurements of variable sources even when their emissions are faint.

Stars Observed: So far, 17 nearby red dwarf stars have been observed as part of the project. However, efforts have focused on three main targets: Barnard's Star (GJ699), Luyten's Star (GJ 273) and Ross 128 (GJ 447).

Table 1 Stars observed as part of Arecibo REDS

Name	Type	D (pc)
GJ 699 (Barnard's Star)	M4V	1.8
GJ 406 (Wolf 359)	M6V	2.4
GJ 411 (HD95735)	M2+V	2.5
GJ 447 (Ross 128)	M4V	3.4
GJ 280 (* alf CMi)	F5IV	3.5
GJ 1111 (G 51-15)	M6.5V	3.6
GJ 273 (Luyten's Star)	M3.5V	3.7
GJ 388 (BD+20 2465)	M4Vae	5.0
GJ 702 (* 70 Oph)	K0-V	5.1
GJ 3379 (G99-49)	M3.5Ve	5.2
2MASS J1835379+325954	M8.5V	5.4
GJ 752 B (VB 10)	M8V	5.9
GJ 222 (* chi01 Ori)	G0V	8.8
GJ 436 (Ross 905)	M3V	10.2
GJ 398 (V* RY Sex)	M4V	15.3
GJ 1115 (BD+35 1890)	K3	26.2
K2-18	M2.5V	38.0

In 2017, two planets were discovered orbiting Luyten's Star [6]. One of these, the outer planet, is in the

habitable zone, a Super-Earth of mass $2.89 M_{\oplus}$ and a period of 18.7 days. Ross 128 has a planet close to the inner edge of the habitable zone, with mass $1.38 M_{\oplus}$ and a period of 9.9 days [7]. A planet was discovered in 2018 around Barnard's Star, with a minimum mass of $3.2 M_{\oplus}$ and a period of 233 days, but it does not lie in the habitable zone [8].

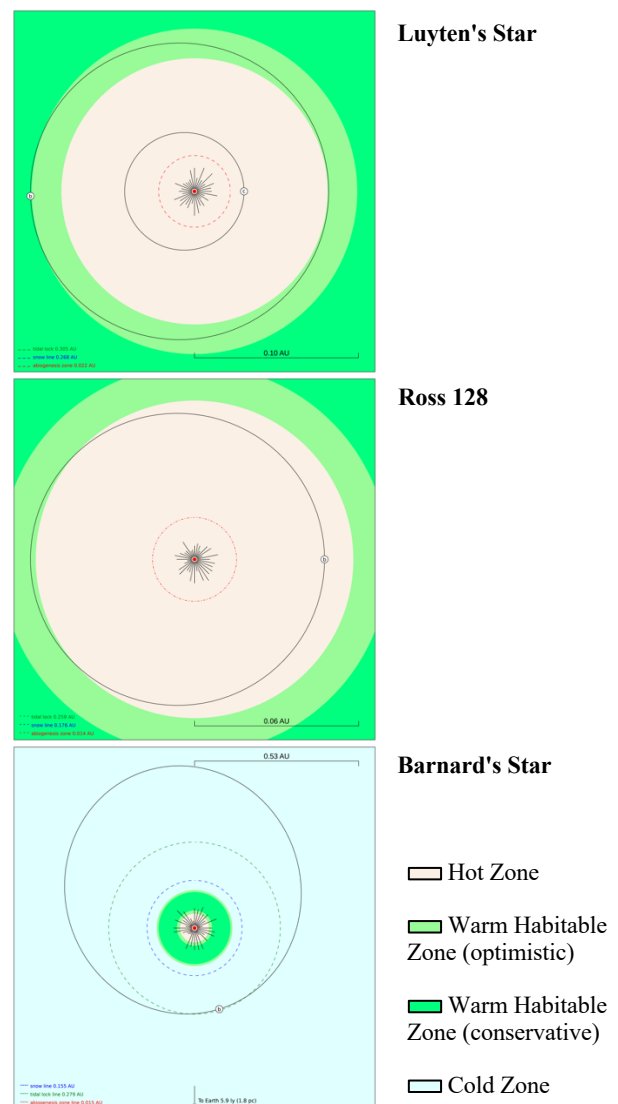


Figure 1: Exoplanet orbits and orbital thermal zones around main target stars.

The main target stars are not known to be particularly active, but even red dwarfs that are not very active, such as Proxima Centauri, are known to emit short-period bursts of about a minute with a peak flux density of 100 mJy, over a 1000 times their quiescent emission [9].

Observation Details: Arecibo is the ideal instrument for these observations as it provides the ability to accurately and sensitively measure rapid source variability thanks to its single, large 305 meter dish. Stellar phenomena such as strong flares and rapid changes in flux densities can be precisely recorded with the instrument, though a trade-off is made with regards to sensitivity to quiescent emissions [10]. Observations have a remarkable temporal resolution of 0.1 s and frequency resolution of ~24 kHz.

Observational Approach. The project's observational approach has centered around carrying out both long (~10 minute) and short (~3 minute) interval observations. Long interval observations allocate a higher proportion of telescope time on-source, allowing a more complete characterization of a star's relative variability and exploiting Arecibo's sensitivity, particularly when various long interval observations are performed back to back. On the other hand, short interval observations allow for more frequent blank-sky (off-source) observations in between each on-source one, which are used to calibrate the on-source observations allowing more precise measurement of absolute fluxes. A mix of both types of interval observations provides the most complete characterizations.

Observations in multiple bands across Arecibo's 1 to 10 GHz range were carried out, as there is less interference at lower frequencies but emissions may be stronger at higher frequencies.

Calibration and Interference Elimination. Switched noise diode calibration was used to measure system temperature. Position switching calibration was used to obtain sufficiently flat baselines for our measurements. Measurements were gain-corrected by bootstrapping off standard continuum source targets with known, stable flux densities, such as quasars (e.g. B1140+223) [11]. Precision of gain-corrections was confirmed by verifying telescope pointing for both target star and calibration continuum source observations..

Radio-frequency interference is minimized by selecting frequencies with minimum interference and recognized by their frequency range and lack of dispersion patterns. Signals of astronomical interest are identified by verifying they do not correspond to recognized radio-frequency interference in form, frequency and range.

Interference due to weather and atmospheric conditions has been identified and ruled out as being of astronomical interest by monitoring changes in temperature, humidity and precipitation at the Observatory, and

correlating these with interference recognized in the observations. This is critical for observations at high frequencies such as those performed in the X band (8 to 10 GHz), as these are particularly susceptible to weather and atmospheric interference.

Results. Short 3 min and long 20-30 min flares in various target stars have been observed, and the three main target stars have been observed for long enough to have initial characterizations of the frequency of their flaring events, presented below. Further results will be released once the analysis of the data is completed.

Conclusion: We have been able to put initial constraints on the radio emissions from two of our main targets. So far, upper bounds on the flaring event frequency have been determined for these stars, shown in Table 2. Results for Ross 128 are still pending further analysis.

Table 2 Initial constraints on activity of target stars

Star	Flaring Time	Total Observed Time	U
GJ 699 (Barnard's Star)	180s	16500s	0.01091
GJ 273 (Luyten's Star)	2400s	26100s	0.09195
GJ 447 (Ross 128)	-	8340s	-

Note: U=Upper bound on frequency of flaring events.

Further characterizing the strength, frequency and spectra of the radio emissions of red dwarfs with potentially habitable planets will enable us to constrain the associated planetary impact and inform the potential for stable habitable conditions. We will model the long term impact of these stellar events on the atmospheric volatiles of their planetary bodies. Furthermore, estimating the water loss rate of these planets, it will be determined which are more likely to retain a large inventory of water today and are therefore the best targets for the search for biosignatures by future missions.

Acknowledgements: This research is funded by the Puerto Rico Space Grant Consortium's Fellowship Program, NASA Grant No. NNX15AI11H. Images in figure 1 are from our *Habitable Exoplanets Catalog*, found at <http://phl.upr.edu/projects/habitable-exoplanets-catalog>.

References: [1] Anglada-Escudé, G. et al. (2016) *Nature*, 536, 437–440. [2] Gillon, M. et al. (2017) *Nature*, 542, 456–470. [3] Zuluaga, J. et al. (2013) *ApJ*, 770, 23. [4] Vidotto et al. (2013) *A&A*, 557, A67. [5] Bolmont, E. et al. (2016) *MNRAS*, 464, 3728–3741. [6] Astudillo-Defru, N. et al. (2017) *A&A*, 602, A88. [7] Bonfils, X. et al. (2017) *A&A*, 613, A25. [8] Ribas, I. et al. (2018) *Nature*, 563, 365–268. [9] MacGregor, M. A. et al. (2018) *ApJL*, 855, L2. [10] Route, M. and Wolsczan, A. (2016) *ApJ*, 830, 85. [11] Salter, C.J. (2000) <http://www.naic.edu/~astro/RXstatus/notes-cjs.ps>