Characterizing the Circumstellar Envelope of AGB star RX Boötis

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Summary: We detected H I 21 cm line emission associated with the circumstellar envelope of the asymptotic giant branch star, RX Boo. The morphology of the circumstellar envelope's H I emission reveals a bow shock and tail structure, implying that it is strongly interacting with the interstellar medium. The envelope morphology spatially mirrors the far-ultraviolet emission from the GALEX satellite.

Background

What are Asymptotic Giant Branch (AGB) Stars and Circumstellar Envelopes?

AGB stars are old post-core helium burning descendants of stars with initial mass of ~0.8-8 $M_{\odot}$. Their contracting inert C-O core raises core the temperature and therefore pressure inside the star. To maintain hydrostatic equilibrium, star's radius enlarge to of order 1 AU and the temperature drops to ~2000-3000 K. The low surface gravity and strong pulsations, along with dust-driven winds, cause substantial outflows of gas and dust produces extensive circumstellar envelopes (CSE).

Why Study the Circumstellar Envelope?

Learning about the chemistry and morphology of the CSEs can give insight into (1) the mass-loss process of AGB stars and (2) how they recycle gas into the galactic environment. AGB stars are major contributors of dust and heavy elements to the galactic environment, producing at least 50% of such material in our galaxy. The H I 21 cm line is a unique tracer since it can probe into distances $\geq 10^{16}$ cm ($\geq 10^3$ AU) away from the star and reveals how it is affected by the interstellar medium (see **Fig. 1**).

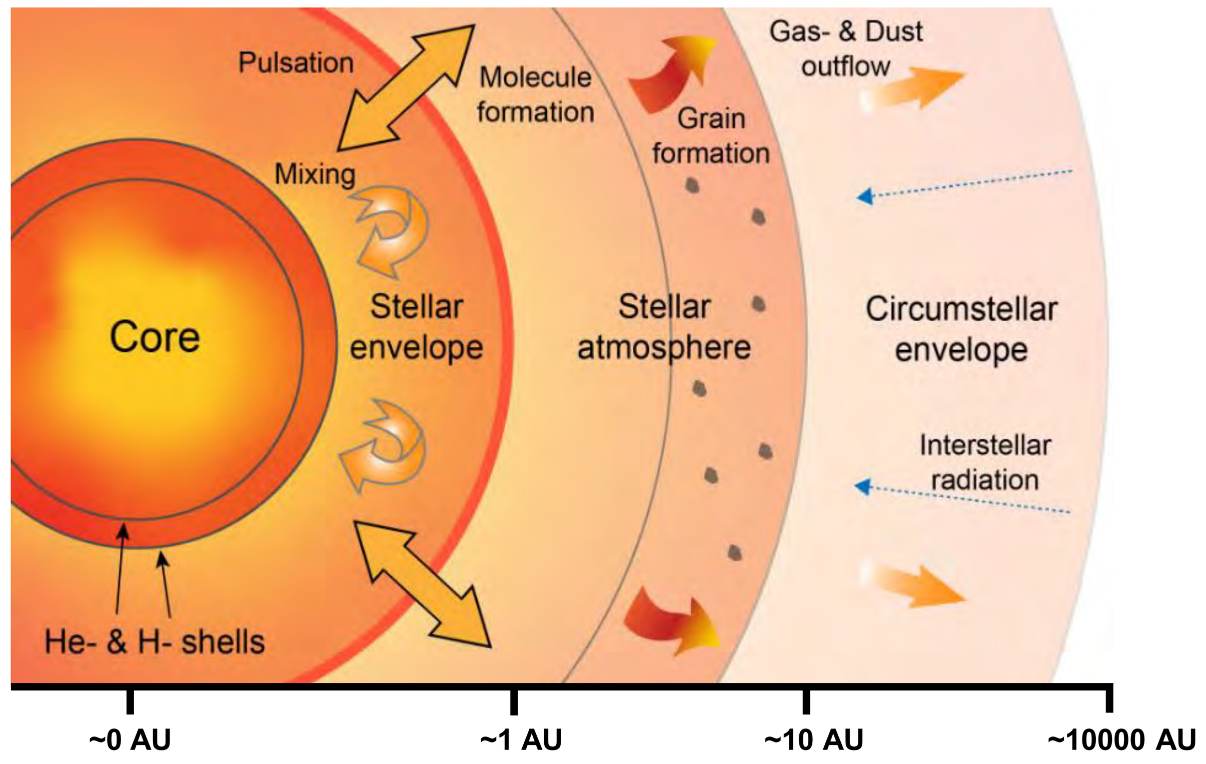
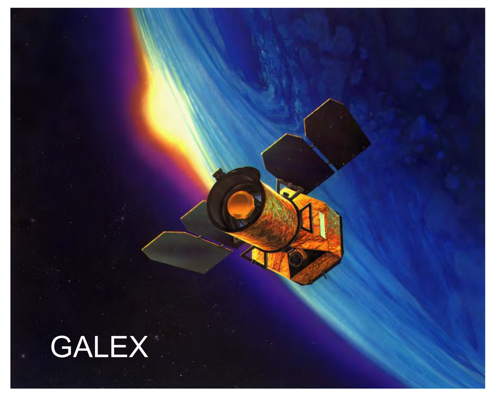


Figure 1: Schematic view of multiple layers within and outside a typical AGB star. From Alm et al. 2019.

Observations

The radio observation of RX Boo was performed by the Karl G. Jansky Very Large Array (JVLA) in the 21 cm line on August 21st, 2014, for 6 hours. The VLA was in the D configuration with a baseline of up to 1 km for resolving the structure of the CSE on the scale of arcminutes and maximum sensitivity to detect extended and faint emission. The spatial resolution at natural weighting was 55.79" × 53.25". For this analysis, the data were calibrated and examined using the Astronomical Image Processing System (AIPS).

An ultraviolet observation was performed by the Galaxy Evolution Explorer (GALEX) on May 6th, 2009. The data were retrieved from the Mikulski Archive for Space Telescope (MAST) database. The image (**Fig. 3**) had an observation time of ~5160 seconds in the far-ultraviolet (FUV) band with an angular resolution of 4.5". The data were processed using DS9 imaging software.



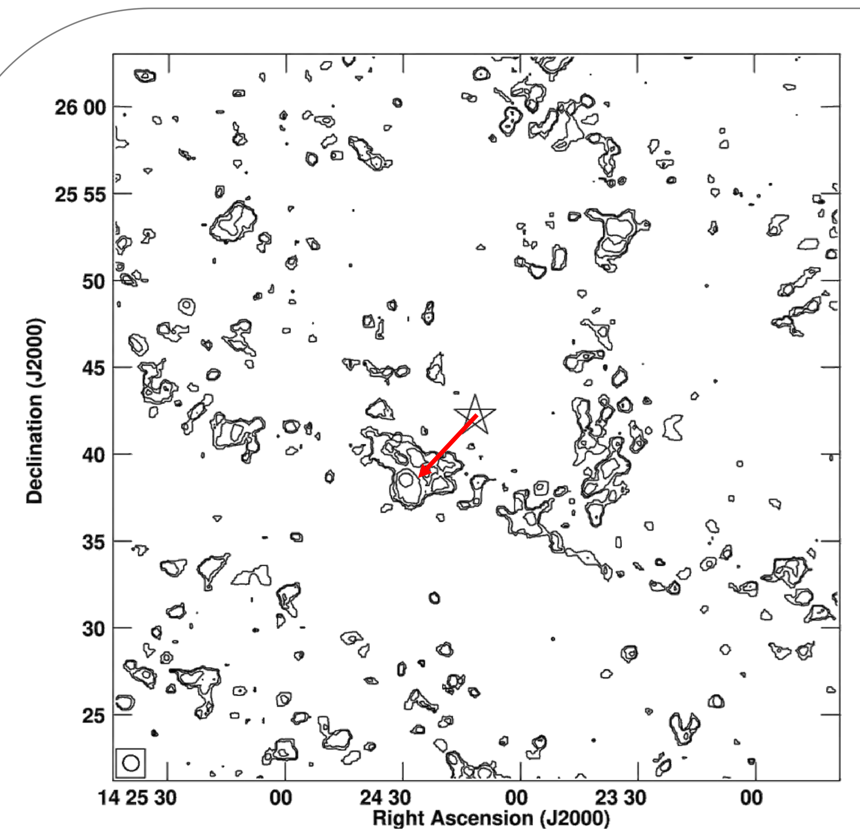


Figure 2: Total intensity moment map of H I with data points omitted below 1.5σ after smoothing by a factor of 3 spatially to minimize noise. The LSR velocities included are from -2.6 km s^{-1} to 4.8 km s^{-1} The contours shown are (1, 2, 4, 8)×3 Jy beam^{-1} m s^{-1}. A star symbol represents the position of the RX Boo, and the arrow represents the velocity direction of space motion.

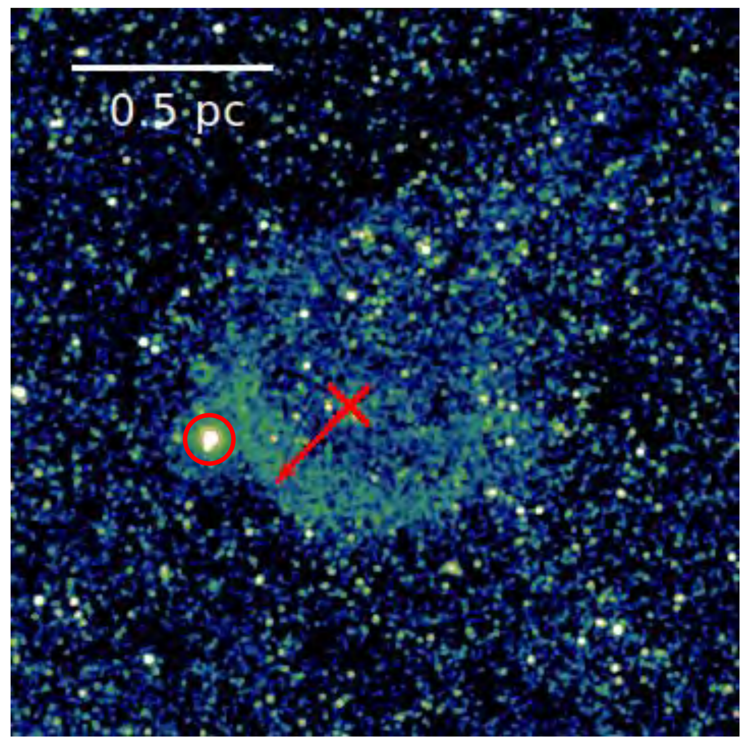


Figure 3: FUV image of RX Boo taken by the *GALEX* satellite. The "x" represents the position of RX Boo, the arrow represents the direction of motion, and the circle encloses a star artifact. The image was processed using DS9 imaging software with gaussian smoothing set to a radius of 13.5".

Complementary Results from GALEX

FUV emission from CSEs are theorized to be caused by the excitation of molecular hydrogen from impacting hot electrons in shocked gas (Martin et al. 2007).

Key results:

• Surprisingly, both radio and FUV data (**Fig. 2** & **Fig. 3**) almost mirror each other, a rare feature amongst CSEs. RX Boo's CSE is most visible as a right-side up bowl structure south of RX Boo and diffuse emission along the northwest direction of the star in both figures.

• The size of the CSE in radio and FUV emission are similar at approximately 0.85 pc and 0.84 pc in diameter, respectively.

• No radio continuum emission was detected from RX Boo or its bow shock.

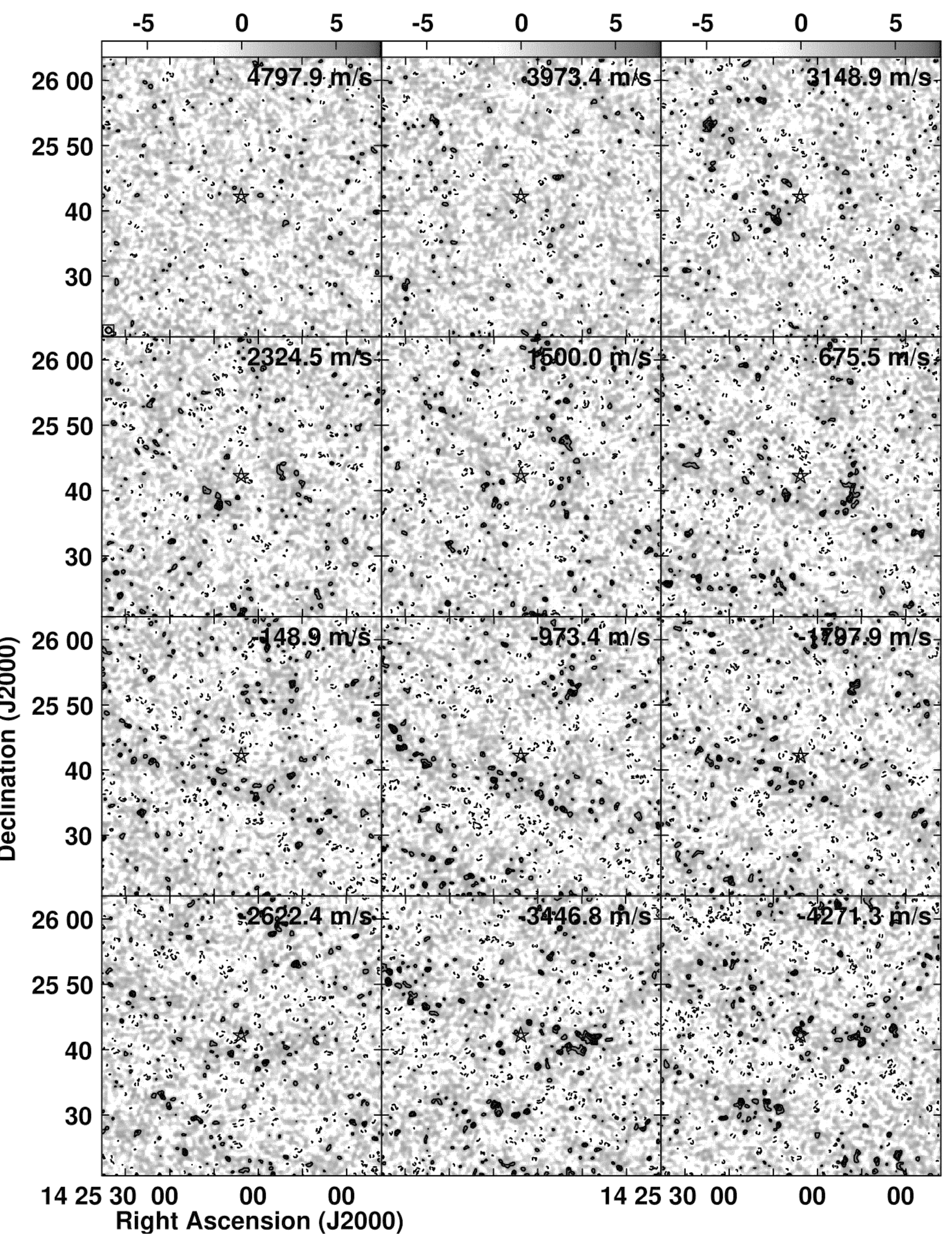


Figure 4: IMAGR contour images of RX Boo observed with the VLA at 21 cm wavelength. H I channel maps are at ~4 km s^{-1} (1.953 kHz) intervals on naturally weighted VLA data. The spatial resolution is 55.79" × 53.25". A star symbol represents the stellar position in each channel. The contour levels shown are (-5, -3.5, -2.5, 2.5, 3.5, 5) × 1.802 mJy beam^{-1} where the positive contours are solid lines and negative contours are shown in dashed lines. IMEAN was used to calculate rms noise, σ, across several spectral channels without CSE and fringe emission.

CSE Morphology and Limitations

Spatially resolved H I emission from the CSE is detected from channel V_{LSR} = 3.1 km s^{-1} to -2.6 km s^{-1}. Unfortunately, contamination from a foreground gas cloud complicates the determination of the total H I gas mass.

Key results:

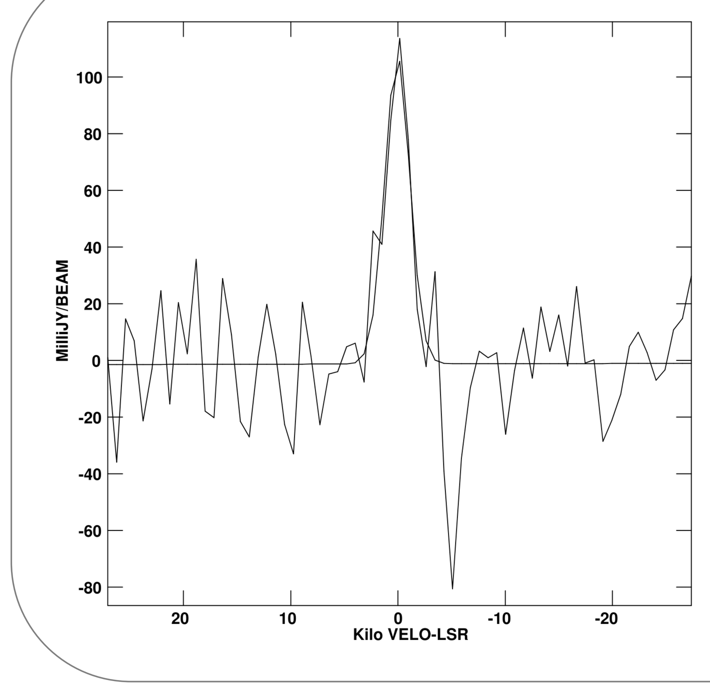
• A hollow and diffuse H I shell is detected in contours ≥ 2.5σ along with a ring or half ring-like structures at LSR velocities 1.5 km s^{-1} to -1.8 km s^{-1}. RX Boo's LSR velocity of 3.86 km s^{-1} is at the upper edge of LSR velocities with CSE emission.

•The high systemic velocity of RX Boo of 43.9 km s^{-1}, with a sky position angle 136° from the vertical (shown in **Fig. 2**), likely displaced the shell through the interstellar medium. This is supported by a diffuse tail end northwest of the star's position in a few of the central channels and the shell is offset in the same direction.

• Fringe structure from an unresolved gaseous cloud along the line-of-site is present in velocity channels ≤ 0.7 km s^{-1}.

• Discerning the CSE from the fringe structure becomes difficult for velocity channels ≤ -2.4 km s^{-1}.

Spectral Analysis



Key results:

• The gaussian model gave values for a calculated estimate for an H I integrated flux density of 0.32±0.037 Jy. This translates to a total atomic hydrogen mass of 0.00184 $M_{\odot}$.

• The model yielded: a peak amplitude of 1.09 mJy, a velocity centroid of 6.45 km s^{-1}, and a FWHM velocity width of 2.78 km s^{-1}.

• Due to high fringe contamination from an unresolved gas cloud, the resulting H I mass calculation should be an overestimate.

Figure 5: CSE emission spectrum of H I on naturally weighted VLA data by integrating the emission in each velocity channel within an 18.5' × 21.33' aperture centered at $\alpha_{J2000} = 14^h\ 24^m\ 11.230^s$ $\delta_{J2000} = 25^h\ 42^m\ 8.4^s$. The smooth line is a gaussian model produced by SLFIT.

Table 1: Stellar Parameters

Star	d (pc)	$\mu_\alpha\cos(\delta)$ (mas yr^{-1})	μ_α (mas yr^{-1})	V_{LSR} (km s^{-1})	$\dot{M}$ ($M_{\odot}$ yr^{-1})	$M_{H\ I}$ ($M_{\odot}$)	T_{eff} (K)
RX Boo	156	19.873	-48.615	3.86	5×10^{-7}	0.00184	3120

Notes – Column Explanations: (1) Name of star; (2-5) Distance, proper motions in right ascension and declination were derived from the GAIA Early Data Release 3 (EDR3); (6) stellar mass-loss from Oloffson et al. 2002.; (8) effective temperature from Takeuti et al. 2013.

Table 2: Instrumentation

Instrument	Band	λ	Δλ	Obs. Time	Resolution
VLA	L	20 cm	2 MHz	6 hr	55.79"×53.25"
GALEX	FUV	1520 Å	268 Å	5160 sec	4.5"×4.5"

Notes – Column Explanations: (1) Instrument for RX Boo observation; (2) frequency range; (3) central frequency; (4) bandwidth; (5) Observation time for RX Boo; (6) Spatial resolution of natural weighting in radio and angular resolution in UV.

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References: Martin C. et al. 2007, Nature, 448, 780; **[Fig. 1]** Alm, M. et al. 2018, Chalmers ODR, 2019, 46; **[Table 1]** Olofsson, H. et al. 2002, A&A, 391, 1053; Takeuti, M. et al 2013, PASJ, 65, 60