THE ASTROPHYSICAL JOURNAL, 384:634–639, 1992 January 10

A VLA 3.6 CENTIMETER SURVEY OF N-TYPE CARBON STARS

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Received 1991 May 20; accepted 1991 July 17

ABSTRACT

We present the results of a VLA continuum survey of 7 N-type carbon stars at 3.6 cm. Evidence exists for hot plasma around such stars; the *IUE* satellite having detected emission lines of singly ionized metals in the optically brightest carbon stars, which in solar-type stars indicate the existence of a chromosphere. In the past, these emission lines have been used to constrain the lower portion of the archetypical chromospheric model of N-type carbon stars, that of TX Psc. Five of the survey stars are semiregular (1 SRa and 4 SRb) variables and two are irregular (Lb) variables. Upper limits of ~ 0.07 mJy are set for the SRb and Lb variables and the lone SRa (V Hya) was detected with a flux of 0.22 mJy. The upper limits for the six stars that are not detected indicate that the temperature in their winds is less than 10^4 K. We also discuss various scenarios for the emission from V Hya and suggest the radio continuum is shock related (either due to pulsation or the suspected bipolar jet) and not due to a supposed accretion disk around an unseen companion.

Subject headings: radiation mechanisms: miscellaneous — radio continuum: stars — stars: carbon — stars: variables: other

1. INTRODUCTION

The cool (N-type) carbon stars offer an interesting probe for the understanding of the chemical evolution of the Galaxy. They are asymptotic giant branch stars, which display strong carbon molecular features in their visual spectra (C_2, CN, and CH) and show a large violet-flux falloff (Alksne & Ikaunieks 1981). The optically brightest N-type carbon stars have been observed with *IUE* and seven (TW Hor, BL Ori, UU Aur, NP Pup, U Hya, T Ind, and TX Psc) show emission features at low resolution (Johnson & Luttermoser 1987). TX Psc (N0; C6, 2) is the only N-type carbon star to be detected with *IUE* at high spectral resolution (Eriksson et al. 1986) and Luttermoser et al. (1989) based a semiempirical chromospheric model (hereafter the LJAL model) of this star on that spectrum. Unfortunately, the chromospheric spectral indicators in the *IUE* spectra only constrain the temperature distribution of the lower chromosphere of the LJAL model; the temperature profile of the upper chromosphere was just a smooth continuation of the lower chromosphere's profile due to the lack of observable (i.e., with *IUE*) spectral lines formed in upper chromospheric regions (e.g., the C II resonance lines near 1335 Å). This TX Psc model chromosphere reaches a maximum temperature of 10^4 K, where hydrogen is 2% ionized. The microwave survey described in this paper was made to determine whether the outermost layers of these stellar atmospheres are, at least, partially ionized. Such detections (or lack thereof) would be invaluable to atmospheric modeling of these peculiar red giants.

Drake, Linsky, & Elitzur (1987) conducted a VLA survey of 22 cool M and C type giants and supergiants at 6 cm and also observed three of these stars at 2 cm. Their sample included nine carbon stars, one S star, and 12 M stars. They detected no point sources from their sample at 6 cm, but had one positive detection at 2 cm (the Mira type star, R Aql, M6.5−9e). They also observed *o* Cet (Mira) at both 2 cm and 6 cm with null results. However, *o* Cet was previously detected at 6 cm with the VLA by Spergel, Giuliani, & Knapp (1983). This suggests that the radio emission from Mira stars may be phase-dependent.

It has been established that some cool carbon stars possess nonradiatively heated regions in their outer atmospheres based on "chromospheric" emission lines seen with *IUE*. These stars also have massive stellar winds as determined from CO observations (Knapp & Morris 1985; Wannier & Sahai 1986; Olofsson, Eriksson, & Gustafsson 1987). An important unanswered question concerning the energetics of these atmospheres is whether any portion of these winds is ionized. This paper reports the results of a cool carbon star survey at 3.6 cm with the VLA. Section 2 details the observation and data reductions. Section 3 discusses our results and their implication for the winds of these cool giant stars. Finally, § 4 presents conclusions of this work.

2. OBSERVATIONS AND DATA REDUCTION

We observed seven N type carbon stars with the NRAO[3] Very Large Array in the BC configuration on 1989 May 21–22. The data were obtained at 3.6 cm using two 50 MHz wide bandpasses centered at 8415 and 8465 MHz. The stellar sample, listed in Table 1, were selected due to their optical brightness, and hence relative proximity. An integration time of roughly 1 hr was used for each object, which set a 3 σ noise level of ~ 0.07 mJy. Coordinates for each object in the sample were taken from the Bright Star Catalogue (Hoffleit 1982) and its supplement catalogue (Hoffleit, Saladyga, & Wlasuk 1983). Five of the stars in our sample are semiregular (SR) variables and two are irregular (L) variables. Of the SR variables, one (V Hya) is an SRa, a class similar to Mira type variables, except

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[3] The National Radio Astronomy Observatory is operated by Associated Universities, Inc., under cooperative agreement with the National Science Foundation.

TABLE 1

THE STELLAR SAMPLE[a]

Star	Catalog Number	α (2000)	δ (2000)	m_v	Spectral Type[b]	Variable Class[b]
W Ori	HR 1648	05h05m23s7	+01°10′39″	6.2	N5; C5, 3	SRb
UU Aur	HR 2405	06 36 32.8	+38 26 43	5.3	N3; C5, 3	SRb
X Cnc	HR 3541	08 55 22.9	+17 13 53	6.6	N3; C5, 4	SRb
U Hya	HR 4163	10 37 33.1	−13 23 04	4.8	N2; C7, 3	Lb
V Hya	SAO 179278	10 51 37.3	−21 15 00	6.8	N6; C6, 5e	SRa
Y CVn	HR 4846	12 45 07.8	+45 26 25	5.0	N3; C5, 4	SRb
TX Psc	HR 9004	23 46 23.4	+03 29 13	5.0	N0; C6, 2	Lb

[a] Data from Hoffleit 1982 and Hoffleit, Saladyga, & Wlasuk 1983, except where indicated.

[b] Spectral and variable classes taken from Alksne & Ikauenieks 1981.

that their peak-to-peak visual light variations are less than 2.5 mag.

The average distance of the Drake et al. (1987) stellar sample is 760 pc, with a carbon star average distance of 940 pc. The N-type carbon stars in our new survey are at an average distance of 360 pc. Thus, these stars should be brighter at radio wavelengths than the Drake et al. sample due to their relative proximity. In addition, the radio continuum from thermal sources is expected to be brighter at 3.6 cm than at 6 cm. Finally, the higher sensitivity of the 3.6 cm receivers will increase the probability of detection.

The data were calibrated using the standard NRAO software and 256 × 256 pixel maps were generated and cleaned with the AIPS package at the University of Colorado. 3C 286 was used for flux calibration with an assumed flux density of 5.27 Jy. Radio maps were examined for point sources at the positions tabulated in the Bright Star Catalogue (Epoch 2000). All seven stars have very small proper motions and their catalogue positions were therefore not corrected for proper motion. The radio reference-frame positions should be accurate to better than 0″2 (Drake et al. 1987). Table 2 includes the measured flux densities S_ν at the nominal source positions (or 3 σ upper limits in the absence of a source) and the K-magnitudes of the sources.

Distances to these sources are somewhat uncertain. N-type carbon stars in the LMC appear to have roughly the same absolute K-magnitude of -8.2 (Cohen et al. 1981). Assuming LMC and Milky Way N stars have similar K-magnitudes, we can use this information to estimate the distances to the N-type stars in our sample. Table 2 lists the derived distances and also lists the effective temperatures of these stars. Two of the stars in our sample have measured angular diameters (in milliarcseconds or mas) from lunar occultation, X Cnc (8.79 ± 1.00 mas) and TX Psc (9.31 ± 0.75 mas) (Ridgway, Wells & Joyce 1977). Using this information and the estimated distances, we can deduce the radii of these stars (see Table 2). The radii of the other stars in our sample are estimated in the following manner. Since we have already assumed that all N-type carbon stars have similar K-magnitudes and a large portion of the stellar flux is emitted in this spectral region, we will *assume* all of these stars have the same luminosity. We then use the blackbody radiation law to determine radius from luminosity and effective temperature. Using TX Psc as the reference star, we deduce the radii from the tabulated effective temperatures (note that this procedure gives 430 $R_\odot$ for X Cnc—within 10% of the actual value).

We now can predict the photospheric flux for these stars at 3.6 cm using equation (4) of Drake et al. (1987),

$$S_\nu = 1.42 \times 10^{-4}\left(\frac{T_b}{10^4\ \mathrm{K}}\right)\phi_*^2 \nu_5^2 , \tag{1}$$

where S_ν is in mJy, $T_b(=T_{\rm eff})$ is the brightness temperature, ϕ_* is the photospheric angular diameter, and ν_5 is the frequency in units of 5 GHz. Table 2 displays this predicted photospheric flux in conjunction with the observed flux (or upper limits). The detected flux for V Hya is an order of magnitude higher than the predicted photospheric flux.

3. DISCUSSION

Drake et al. (1987) also present two equations to determine the radio flux from a partially ionized wind. For an optically

TABLE 2

THE RADIO OBSERVATIONS

Star	K-magnitude	$R/R_\odot$	d (pc)	$T_{\rm eff}$(K)[a]	Photospheric S_ν(mJy)	Observed S_ν(mJy)
W Ori	−0.27[b]	430	390	2620	0.011	≤0.072
UU Aur	−0.61[c]	370	330	2825	0.014	≤0.070
X Cnc	0.37[b], 0.19[c]	470	500	2600	0.009	≤0.075
U Hya	−0.60[c]	370	330	2825	0.014	≤0.070
V Hya	−0.31[c]	420	380	2650[d]	0.013	0.22 (9 σ)
Y CVn	−0.72[c]	390	310	2730	0.017	≤0.065
TX Psc	−0.66[b], −0.76[c]	310	315	3070	0.012	≤0.071

[a] Tsuji 1981, except where indicted.

[b] Walker 1980.

[c] Bergeat & Lunel 1980.

[d] Lambert et al. 1986.

thick wind,

$$S_\nu = 1.6 \times 10^{11}\left(\frac{\dot{M}_{\rm ion}}{v_W}\right)^{1.33} D^{-2} v_5^{0.6} T_4^{0.1} , \quad (2)$$

and for an optically *thin* wind,

$$S_\nu = 4.4 \times 10^{20}\left(\frac{\dot{M}_{\rm ion}}{v_W}\right)^{2} D^{-2} v_5^{-0.1} T_4^{-0.35} R_*^{-1} , \quad (3)$$

where $\dot{M}_{\rm ion} \equiv f_{\rm ion}\, \dot{M}_{\rm total}(f_{\rm ion} \ll 1)$ is the mass-loss rate for the ionized material in $M_\odot$ yr^{-1}, v_W is the wind velocity in km s^{-1}, D is the distance in kpc, T_4 is the wind temperature in 10^4 K, and R_* is the photospheric radius in solar radii. Using the LJAL model of TX Psc, we now calculate the predicted radio flux of this model. We use a mass-loss rate of 4×10^{-7} $M_\odot$ yr^{-1} and a wind speed of 12.5 km s^{-1} (Eriksson et al. 1986) for TX Psc. For the maximum temperature (10^4 K) and corresponding ionization fraction (0.02) of the LJAL model, an optically thick wind should emit a flux of 1.3 mJy (20 times the upper limit) at 8.44 GHz, and for an optically thin wind, a flux of 5.6 mJy (80 times the upper limit). The uppermost layers ($T > 6000$ K) of the LJAL model cannot be correct. Therefore, the chromospheres and winds of these non-Mira carbon stars must be cooler (i.e., $T < 10^4$ K) than assumed in the model for TX Psc.

As can be seen in Table 2, we detected one of the seven stars in our sample—the SRa variable, V Hya. V Hya was at maximum light (phase 0) on 1988 September 13 with $m_V = 7.0 \pm 0.2$ (Mattei 1990, private communication), which puts the star at phase 0.53 ($P \simeq 530$ days) in its visual light curve on the observation date. This phase, in Mira type variables, does not correlate with maximum visual magnitude, maximum Balmer emission, or maximum Mg II emission. V Hya has a known companion star; however, it lies 46″.0 away from the carbon star at a position angle of 186°, and is thus well separated from V Hya in our map. Figure 1 shows the VLA map of V Hya with contours at integer multiples of the 2 σ level, the crosshair marks the optical position of V Hya. Note that a 6 σ contour is visible just westward (to the right) of the crosshair. The observed flux is 0.22 ± 0.01 mJy, which corresponds to a 9 σ source.

Is this radio emission due to an outward propagating shock or is this star peculiar? We now examine some other observational traits of V Hya. The CO emission seen in V Hya is not "typical" for Mira like or SRa-like variables. Tsuji et al. (1988) have detected asymmetries in the CO $J = 1$–0 (115271.204 MHz) emission line of V Hya and attribute it to a bipolar outflow. Kahane, Maizels, & Jura (1988) made a similar discovery and tried to explain the bipolar flow by giving V Hya a high rotational velocity ($v \sin i = 15 \pm 5$ km s^{-1}). They suggested this high velocity was induced via tidal spin-up by a nearby, unseen companion. The high velocity was deduced by noting the visual and near-IR spectrum of V Hya has broadened molecular features with respect to "typical" N-type carbon stars. They used U Hya as a template and convolved its spectrum with a Gaussian filter at various velocity dispersions until the U Hya spectrum matched the V Hya spectrum. However, this analysis is flawed, since they are making a comparison between two very different types of star. V Hya is an N6 (very cool and/or high C/O ratio—see Luttermoser 1988) carbon star and an SRa (almost Mira-like) variable, whereas U Hya is an N2 (i.e., warmer) carbon star and an Lb variable. Although the effective temperature difference between these

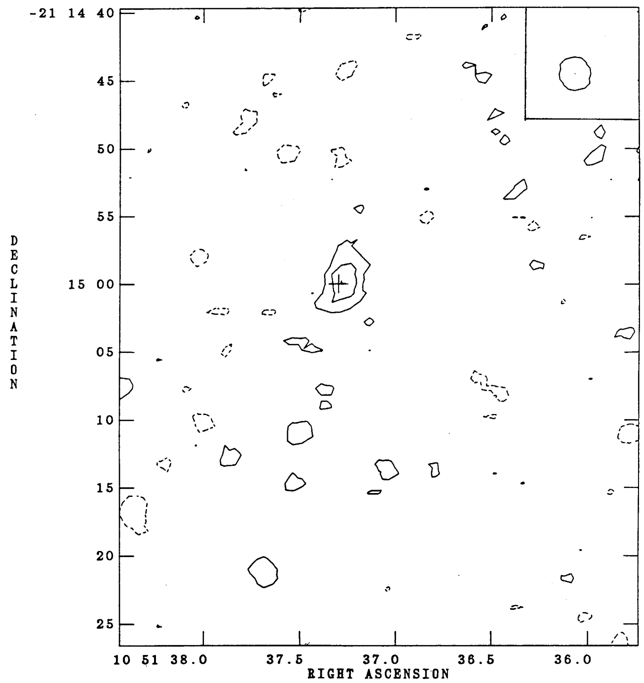

FIG. 1.—VLA contour map of V Hya at 3.6 cm with integer multiples of 2 σ plotted. The cross marks the visual stellar position (epoch 2000). The inset shows the 50% of peak beam profile (~2″.25).

two stars is only ~200 K, it is significant to the line opacities in these stellar atmospheres. V Hya also has a higher C/O ratio in comparison to U Hya (1.05 as compared to 1.04, Lambert et al. 1986). As pointed out by Johnson, Luttermoser, & Faulkner (1988), as carbon enhancement proceeds for a given effective temperature, CO cooling extends deeper into the atmosphere, leading to an increasingly wider cool layer, which enhances the opacity in neutral metal and molecular lines. Recent spectra obtained in the Hα region for a sample of N-type carbon stars (Luttermoser 1991, in preparation) show that UU Aur and Y CVn (i.e., two "typical" carbon stars) have much broader absorption features than U Hya. Both UU Aur and Y CVn are N3 carbon stars and SRb variables. The broader features of these cooler, semiregular carbon stars are more likely due to lower temperatures and (perhaps) higher densities than the warmer, irregular variable U Hya and not due to rotation. Of course, this still leaves the mystery of why V Hya displays a bipolar outflow. Sahai & Wannier (1988) detected high-velocity (up to ~120 km s^{-1}), blueshifted CO features in a 4.5 μm spectrum of V Hya and suggested an accretion disk wind from an enveloped companion could be the cause of the velocity components.

Evans (1990) has noted peculiarities in the optical spectra of V Hya as well. The emission spectrum in the blue-violet region differs from that of typical Mira-type variables: The emission features are those of forbidden Si II and Fe II instead of the fluoresced Fe I and Mn I emission features of "normal" Miras. Also, the Ca II H and K lines are strong emission lines, whereas typically only small or no emission "bumps" are seen in most Miras. The forbidden emission lines are shifted by 155 km s^{-1} blueward with respect to the radial velocity of the star. Evan's analysis leads him to conclude that the features seen are the result of shock excitation in a jet-circumstellar shell interface.

Is our radio detection due to an accretion disk, jet-shock, or pulsation-shock? We have searched the *IUE* archives and found a low-resolution, long-wavelength spectrum (LWP 14524). This observation was made on 1988 November 24 under observing program LGKMJ and corresponds to phase 0.12 in its light curve. V Hya on this data displayed a Mg II emission feature with an integrated flux of 1.6×10^{-13} ergs s^{-1} cm^{-2}. This flux is consistent with the observed Mg II flux of other bright N-type stars and other Mira type variables. Johnson & Luttermoser (1987) list the integrated Mg II flux for seven N-type carbon stars including UU Aur (2.2×10^{-13} ergs s^{-1} cm^{-2}), U Hya (2.7×10^{-13} ergs s^{-1} cm^{-2}), and TX Psc (2.3×10^{-13} ergs s^{-1} cm^{-2}) of our sample. Since the Mg II flux is consistent with the other bright N-type stars (all of similar distance), we feel that the accretion disk scenario for V Hya is not well substantiated in UV light.

While our radio detection of this star could be interpreted as accretion disk emission, an outward propagating shock could give rise to such radio emission. As mentioned earlier, at least two Miras have been detected in the radio continuum, and one of these (*o* Cet) has been observed a second time with no detection. This may indicate that radio continuum detections are phase-dependent for the Miras and SRa variables. We test this scenario with a simplistic estimate of the radio emission from a pulsation shock.

We use an outward-propagating, spherical shock model for V Hya to calculate the flux received by an observer at a great distance D from the star by using the (p, z) coordinate system (see Figure 7-27 of Mihalas 1978), where the *impact parameter* p is the perpendicular distance of a ray from a parallel ray passing through the center of the star, and the *distance along the ray* z is measured from the plane through the center of the star perpendicular to the central ray. Note that $z = r \cos\theta$ and $p = r \sin\theta$, where r is the radial distance from stellar center. We treat the shock as a hollow shell whose sole opacity source at radio frequencies is hydrogen free-free absorption, and we ignore any free-free emission from the stellar photosphere. G. H. Bowen (1990, private communication) has kindly provided us with two hydrodynamic model atmospheres of a pulsating red giant star with the characteristics of V Hya. These models have a pulsation period of 520 days, $R = 420\ R_\odot$, $T_{eff} = 2650$ K (see Table 2), and $M = 2\ M_\odot$ (Aaronson & Mould 1985; Catchpole & Feast 1985). The models are further constrained such that the outflow terminal velocity is ~ 26 km s^{-1} (Zuckerman & Dyck 1989) with a mass-loss rate of $\sim 9.2 \times 10^{-6}\ M_\odot\ yr^{-1}$ (Skinner & Whitmore 1988). The procedure used to generate these dynamic models can be found in Bowen (1988). Model 1 incorporates a sinusoidal piston at the base with a 4.0 km s^{-1} amplitude, which results with a mass-loss rate of $3.3 \times 10^{-6}\ M_\odot\ yr^{-1}$ and terminal velocity of 26 km s^{-1}. Model 2 has 4.5 km s^{-1} amplitude piston, which results in a mass-loss rate of $1.0 \times 10^{-5}\ M_\odot\ yr^{-1}$ and a terminal velocity of 26 km s^{-1}. For each model, we select two different pulsational phases (0.5 and 0.625), which should roughly correspond to V Hya's visual light phase of our observation.

At radio wavelengths, hydrogen free-free absorption is the dominant opacity source for warm ($T > 5000$ K) gas, where the absorption coefficient is expressed as (e.g., Spitzer 1978, eq. [3.57])

$$\kappa_{ff} = 0.1731\left[1 + 0.130 \log\left(\frac{T^{3/2}}{\nu}\right)\right]\frac{n_e n_p}{T^{3/2}\nu^2}\ \mathrm{cm}^{-1} . \quad (4)$$

At this point, we make a further assumption that all the free-free emission originates in the innermost, hottest shock of the dynamic models. We then can simplify this expression for our specific case by noting that ν is essentially constant ($\nu = 8.44 \times 10^9$ Hz) through our bandpass and that the temperature extremes in the spatial region of the innermost shocks of the Bowen models are 1200 and 6000 K. For these temperatures, the expression $0.130 \log(T^{3/2}/\nu)$ ranges between -0.69 and -0.55, and for this simplified analysis, we set this expression to a constant of -0.62. The quantity κ_{ff} then simplifies to

$$\kappa_{ff} \approx 0.066 \frac{n_e n_p}{T^{3/2}\nu^2} . \quad (5)$$

The observed flux per unit receiver area from this shock can be expressed as (e.g., Mihalas 1978, eq. [7.185])

$$f_\nu = \frac{2\pi}{D^2}\int_0^\infty I_\nu(p, \infty) p\, dp . \quad (6)$$

Assuming thermal emission and that the electrons and protons have Maxwellian velocity distributions, we can write the emergent intensity as (e.g., Mihalas 1978, eq. [7.184])

$$I_\nu(p, z=\infty) = \int_{-\infty}^{\infty} B_\nu[T(p, z)] e^{-\tau(p,z)} \kappa_{ff}(p, z) dz ,$$
$$\approx \frac{0.13k}{c^2}\int_{-\infty}^{\infty} \frac{n_e(p, z) n_p(p, z)}{\sqrt{T(p, z)}} e^{-\tau(p,z)} dz . \quad (7)$$

We now set $n_e = f_e n_H$ and $n_p = f_i n_H$, where f_e is the electron fraction, f_i is the hydrogen ionization fraction ($\neq f_e$, in these models), and n_H is the total hydrogen density [cm^{-3}]. We select three depths from the Bowen models, T_{max} just behind the innermost shock (shock zone 1), T_{min} just in front of this shock (shock zone 3), and the depth in between these two (shock zone 2) as tabulated in Table 3. We next treat the integral in equation (7) as a sum and ignore the emission contribution from the shock on the back side of the star. Equation (7) now becomes

$$I_\nu(p, \infty) \approx \frac{0.13k}{c^2}\sum_{j=1}^{3} \Phi_j \Delta z_j . \quad (8)$$

The term Φ is defined as

$$\Phi \equiv \frac{f_e f_i(p, z) n_H^2(p, z)}{\sqrt{T(p, z)}} e^{-\tau(p,z)} , \quad (9)$$

where $f_e f_i$ is determined from the Saha equation (assuming $f_i \ll 1$)

$$f_e f_i = \frac{2.41 \times 10^{15}}{n_H} T^{3/2} e^{-1.58\times 10^5/T} , \quad (10)$$

and Δz is the path length through a zone along the ray z

$$\Delta z_j = \frac{l}{\cos\theta} = l\frac{r}{\sqrt{r^2 - p^2}} , \quad (11)$$

between the limits of $p = 0$ to $p = r$ (zone 1). The parameter l is the thickness of the zone in question and r is the radial distance of that zone. We define R_{sh} as r (zone 1) from this point on. The

TABLE 3

PULSATION SHOCK MODEL DATA

PARAMETER	PHASE 0.500 Zone 1	PHASE 0.500 Zone 2	PHASE 0.500 Zone 3	Phase 0.625 Zone 1	Phase 0.625 Zone 2	Phase 0.625 Zone 3
			Model 1			
T (K)	6008.4	4042.5	1369.1	3367.8	2197.9	1318.8
r (10^{13} cm)	5.251	5.468	5.774	6.054	6.315	6.733
l (10^{12} cm)	1.65	2.17	3.06	3.46	2.61	4.18
u (km s^{-1})	8.06	9.82	7.01	10.3	11.4	8.95
N_H (10^9 cm^{-3})	7.91	4.88	1.86	4.70	2.29	0.879
$f_e f_i$	0.539	1.35 (−6)	4.99 (−40)	4.23 (−10)	6.53 (−21)	1.22 (−41)
κ_{ff} (cm^{-1})	6.71 (−8)	1.16 (−13)	3.16 (−47)	4.43 (−17)	3.08 (−28)	1.83 (−49)
$\tau(p = \frac{1}{3}R_*)$	1.1 (5)	0.26	9.8 (−35)	1.6 (−4)	8.1 (−16)	7.7 (−37)
$\tau(p = \frac{2}{3}R_*)$	1.2 (5)	0.27	1.0 (−34)	1.6 (−4)	8.5 (−16)	8.0 (−37)
$\tau(p = R_*)$	1.3 (5)	0.30	1.1 (−34)	1.8 (−4)	9.1 (−16)	8.5 (−37)
$\tau(p = R_{sh})$	1.2 (6)	0.90	2.3 (−34)	1.0 (−3)	2.8 (−15)	1.8 (−36)
S (mJy)		0.076			2.2 (−5)	
			Model 2			
T (K)	4806.5	2425.4	1218.0	2680.2	2662.2	1966.9
r (10^{13} cm)	5.312	5.520	5.963	5.734	6.045	6.371
l (10^{12} cm)	1.63	2.08	4.43	2.06	3.11	3.26
u (km s^{-1})	7.46	7.91	4.63	7.95	9.99	9.07
N_H (10^9 cm^{-3})	28.3	11.5	4.92	16.0	13.4	6.24
$f_e f_i$	1.50 (−4)	1.28 (−18)	9.58 (−47)	5.23 (−16)	4.15 (−16)	4.37 (−25)
κ_{ff} (cm^{-1})	3.35 (−10)	1.31 (−24)	5.06 (−53)	8.93 (−22)	5.02 (−22)	1.81 (−31)
$\tau(p = \frac{1}{3}R_*)$	560	1.6 (−11)	2.3 (−40)	3.5 (−9)	1.6 (−19)	6.0 (−19)
$\tau(p = \frac{2}{3}R_*)$	590	1.7 (−11)	2.3 (−40)	3.6 (−9)	1.7 (−9)	6.3 (−19)
$\tau(p = R_*)$	660	1.8 (−11)	2.5 (−40)	4.0 (−9)	1.8 (−9)	6.7 (−19)
$\tau(p = R_{sh})$	8.2 (3)	2.7 (−11)	3.5 (−40)	2.3 (−8)	4.9 (−9)	1.4 (−18)
S (mJy)		0.11			3.5 (−10)	

observed flux (i.e., eq. [6]) now can be written as

$$f \approx \frac{2\pi}{D^2} \int_0^\infty \frac{0.13k}{c^2} \left(\sum_{j=1}^{3} \Phi_j \Delta z_j \right) p\,dp$$
$$\approx \frac{0.26\pi k}{c^2 D^2} \int_0^{R_{sh}} p\,dp \sum_{j=1}^{3} \Phi_j z_j \,, \qquad (12)$$

where the ν subscripts are now neglected, since the intensity is only slowly varying in frequency. We now rewrite the integral above as a sum and chose the following four impact parameters as the summation points: $p = \frac{1}{3}R_*$, $\frac{2}{3}R_*$, R_*, and R_{sh}. Since radio fluxes are measured in units of Janskys (1 Jy = 10^{-23} ergs s^{-1} cm^{-2} Hz^{-1}) and symbolized by an S_ν, we now express the flux equation in units of milli-Janskys with the relation S (mJy) = $10^{26} f$. The flux can now be written as

$$S(\text{mJy}) = 1.25 \times 10^{-11} \frac{R_*^2}{D^2} \sum_{i=1}^{4} \sum_{j=1}^{3} \Phi_j l_j \times \frac{r_j}{\sqrt{r_j^2 - p_i^2}} \frac{p_i}{R_*} \frac{\Delta p_i}{R_*} \,, \qquad (13)$$

where Δp_i has the values of $\frac{1}{2}R_*$, $\frac{1}{2}R_*$, $R_{sh} - R_*$, and r (zone 3) − r (zone 1) for the four summation points. Table 3 displays the various calculated parameters used in determining this flux. The high opacity through the shock *at phase 0.500* justifies our neglect of the contribution from the distant hemisphere of these models. The highest temperature zone has an extremely high optical depth. To estimate the emergent intensity from this zone, we assume the opacity is uniform between this depth point and the adjacent outer depth and scale the path length (i.e., Δz) to optical depth unity. We then sum over three such subshells to determine the contribution to the emergent intensity from the optically thick shell. This demonstrates the difficulty in performing radiative transfer calculations in dynamic stellar atmospheres—a very find grid of zones is required in large shocks to properly determine the intensity from the shock. Model 1 at phase 0.500 predicts a flux of 0.076 mJy, a factor of 3 smaller than the observed value; while model 2 at phase 0.500 gives a flux of 0.11 mJy (2 times smaller). The shocks at the 0.625 pulsational phases are optically thin in this analysis and the fluxes calculated are negligible to the predicted photospheric flux.

Although our calculated fluxes are 2–3 times smaller than the observed flux, we remind the reader that our analysis is very crude (i.e., LTE ionization, uncertainties in the stellar parameters, approximate treatment of radiative transfer, etc.), and assert that free-free emission from a pulsational shock is consistent with the observed radio signal. Shocks resulting from bipolar jets could probably also give rise to this emission as well. We do not attempt a test calculation for this scenerio due to the lack of information on the structure of the bipolar jets.

4. CONCLUSIONS

We have surveyed a group of optically bright, cool carbon stars with the VLA at 3.6 cm. We detected one out of seven stars—the lone "Mira-like" star in our sample. This detection, along with previous, intermittent Mira star detection at radio wavelengths, may indicate that the radio flux is phase dependent. It has been shown by various authors (e.g., Merrill 1940; Wood 1979; Willson, Wallerstein, & Pilachowski 1982; Bowen 1988) that shock waves are produced in the long-period–

variable stellar atmospheres as the star pulsates. A simplistic calculation of the free-free emission from shocks in hydrodynamic models representative of V Hya is consistent with the VLA observations. V Hya, however, is a very *peculiar*, peculiar red giant and its radio emission could be the result of shock heating in the bipolar jets seen in CO observations. An accretion disk in this system (as suspected by some authors) could also give rise to such emission, but the UV spectrum of this object shows no evidence for such a disk. We also show that the "spun-up" model of V Hya by Kahane et al. (1988) is not appropriate. As mentioned earlier, both UU Aur and Y CVn have broadened photospheric absorption features as compared to U Hya. If this implies a high rotational velocity caused by a "spin-up" by an unseen companion, as Kahane et al. suggest, one might expect radio emission from these stars as well (none was seen). A monitoring program for V Hya at radio frequencies over a few photometric cycles ($P \simeq 530$ days) would help clarify the physical process that gives rise to this emission, and ideally, simultaneous observations of CO and visual/IR photometry, would lead to a global model for this star. Finally, the non-Mira carbon stars in our sample have no detectable signal, which indicates that the chromospheres and winds of these types of stars are cooler than 10^4 K.

We would like to thank NASA for grant NAG5-1305 to support of this research and NRAO for carrying out the observations for this program (project code AL191). We greatly appreciate the use of the *IUE* Regional Data Analysis Facility at the University of Colorado operated under the NASA contract NAS5-28731. We wish to thank J. L. Linsky and P. G. Wannier (the referee) for useful comments of this manuscript. Finally we especially would like to thank Janet Mattei of the AAVSO for information on the photometry of V Hya and G. H. Bowen for supplying us with an unpublished hydrodynamic model of V Hya.

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