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405 HILGARD AVENUE
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March 17, 1992

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Valorie A. Burr
National Aeronautics and Space Administration
Goddard Space Flight Center
Greenbelt, MD. 20771

Dear Ms. Burr:

Enclosed please find a copy of the report from principal investigator Michael Jura in reference to grant NAG 5 1406.

Thank you for your patience in receiving this report.

Sincerely,

Sheila Altemus

Sheila Altemus
Department of Astronomy

cc: Linnaea Lewis
Grant Officer
OCGA/UCLA

(NASA-CR-190161) CARBON STARS WITH OXYGEN-RICH CIRCUMSTELLAR MATERIAL (California Univ.) 25 p

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UCLA: DEPARTMENT OF ASTRONOMY
156205

To: Ms. Cheryl Tyler
From: Michael Jura, Professor, Astronomy
Date: February 19, 1992
Re: Technical Report, NAG 5 1406

This note is written in response to the request from Valorie Burr of NASA regarding a technical report on NAG 5 1406. Enclosed is a draft of a paper that was submitted to the Astrophysical Journal on January 16, 1991. After about 6 months, we received negative reports from the referees about this paper. Therefore, in order to finish this project, it will be necessary to redo the paper. I have not submitted a final report on this subject because we are not yet finished. When we do have the time, we will revisit this issue and be more quantitative about the synthesis of oxygen-rich molecules in carbon-rich chemical environments. We are not yet finished, but I hope that you understand that we have worked hard on this project.

Jura/Hawk...
5-1-91

CARBON STARS WITH OXYGEN-RICH CIRCUMSTELLAR MATERIAL

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ABSTRACT

We have used the IUE satellite to search for companions to two carbon-rich stars with oxygen-rich circumstellar envelopes, EU And and V778 Cyg. Depending upon the amount of interstellar extinction and distances (probably between 1 and 2 kpc from the Sun) to these two stars, we place upper limits between $\sim$1.5 and $\sim$6 $M_{\odot}$ to the mass of any main sequence companions. For the "near" distance of 1 kpc, it seems unlikely that there are white dwarf companions because we would expect to detect ultraviolet emission from accretion of red giant wind material onto the white dwarfs.

We propose a new model to explain the oxygen-rich envelopes. If these stars have a high nitrogen abundance, the carbon that is in excess of the oxygen may be carried in the circumstellar envelopes in HCN rather than C_2H_2 which is a likely key seed molecule for the formation of carbon grains. Consequently, carbon particles may not form; instead, oxygen-rich silicate dust may nucleate from the SiO present in the outflow.

Subject headings: interstellar: grains - stars: carbon - stars: circumstellar shells - ultraviolet: spectra

I. INTRODUCTION

Essentially all high-luminosity carbon stars lose mass at rates greater than 10^{-7} $M_\odot$ yr^{-1} (Jura 1991a). Almost always, the circumstellar matter surrounding carbon stars is carbon-rich. However, Little-Marenin (1986) and Willems & de Jong (1986) discovered from analysis of the LRS (Low Resolution Spectrograph) on IRAS that a few carbon-rich stars have circumstellar dust that is oxygen-rich. Further observations confirm that at least some of the circumstellar gas is oxygen-rich because it exhibits OH and H_2O maser emission (Benson & Little-Marenin 1987, Nakada *et al.* 1988, Deguchi *et al.* 1988, Little-Marenin *et al.* 1988, Maizels *et al.* 1991).

One possible explanation for the carbon stars with oxygen-rich circumstellar envelopes is that during the past 50 years or so, their outer layers switched from being oxygen-rich to being carbon-rich (Willems & de Jong 1986, 1988, Chan & Kwok 1988). A severe difficulty with this "switching" hypothesis is that it requires at least a factor of 10 more high luminosity carbon stars than are observed (Claussen *et al.* 1987, Lambert, Hinkle & Smith 1990, Zuckerman & Maddalena 1989) although this point is disputed (de Jong 1989). Another hypothesis is that these carbon-rich stars with oxygen-rich circumstellar envelopes are the consequence of binary interactions of some sort (Benson & Little-Marenin 1987, Lloyd Evans 1990, Morris 1987, Lambert *et al.* 1990, Maizels *et al.* 1991).

Carbon stars are very faint in the ultraviolet (Johnson & O'Brien 1983), and a search for companions at these wavelengths can reveal objects which are otherwise undetectable. We have used the IUE satellite to search for such companions around two of the brightest carbon-rich stars with oxygen-rich circumstellar envelopes. Our upper limits to the ultraviolet flux can be used to constrain the amount of emission (i) from the photosphere of any main sequence companion, or (ii) from the accretion flow onto a white dwarf companion.

II. THE STARS

We obtained IUE data for two carbon rich stars with oxygen-rich envelopes: EU And and V778 Cyg. Here we describe our estimates for the relevant parameters needed to analyze the data.

Noguchi *et al.* (1990) have measured a K-band magnitude for V778 Cyg of 3.54 mag. If we assume an extinction at K of 0.15 mag/kpc (see Jura, Joyce & Kleinmann 1989) and an absolute K band magnitude for carbon stars of -8.1 (see Claussen *et al.* 1987), the distance to this star is 1.9 kpc. This distance compares reasonably well with the estimate given by Peery (1975) of 1.4 kpc.

For EU And, Noguchi *et al.* (1990) measured $m_K = 3.79$ mag. Using the same procedure for this star as we did for V778 Cyg, we estimate a distance of 2.1 kpc.

The indicated distances for both of these stars and their observed galactic latitudes imply that they lie at distances, Z, from the plane of the Milky Way of more than 400 pc. Similarly, using a similar analsysis and the available photometry, the four other well studied carbon stars with oxygen-rich envelopes, BM Gem, C1003, MC79-11 and FJF270 (Noguchi *et al.* 1990, Le Bertre, Deguchi & Nakada 1990) lie at nominal distances from the galactic plane of 400, 200, 560 and 300 pc, respectively. As a first approximation, we can represent the space density, ρ, of stars from the galactic plane as:

$$\rho = \rho_0 \ \exp(-Z/|Z_0|) \tag{1}$$

where Z_0 is the exponential scale height from the galactic plane. Because all these distances from the plane are greater than or equal to the exponential scale height for carbon stars of $Z_0 = 200$ pc derived by Claussen *et al.* (1987), it is possible that the carbon-rich stars with oxygen-rich envelopes are derived from a different population than "normal" carbon stars. Therefore, we also consider the possibility that EU And and V778 Cyg lie at a distance of 1 kpc from the Sun, about a factor of 2 closer than the values derived above. We analyze these stars for both a "near" and "far" distance.

Using $A_K = 0.15$ kpc^{-1} and the interstellar extinction curve given by Savage & Mathis (1979) such that $\tau(2800\ \text{Å})/\tau(\text{K}) = 16$, we estimate $A_{2800} = 2.4$ mag kpc^{-1}. According to Spitzer (1978), the average value of E(B-V) is 0.61 mag kpc^{-1} which leads to $A_{2800} = 3.8$ mag kpc^{-1} for the extinction curve given by Savage & Mathis(1979). Here, we adopt a constant value of $A_K = 2.4$ mag kpc^{-1} (corresponding to $\tau(\text{K}) = 2.2$). This average might be too low for the galactic plane, but much of the lines of sight to EU And and V778 Cyg lies above the galactic plane and away from the bulk of the interstellar dust.

To estimate the amount of circumstellar extinction, we follow the analysis given in Jura (1986). We assume that the total mass loss rate, dM/dt ($M_\odot$ yr^{-1}), is given by the expression:

$$dM/dt = 1.1 \times 10^{-8}\, v_\infty\, D^2\, L_4^{-1/2}\, F_\nu(60)\, \lambda_{10}^{1/2} \tag{2}$$

In this expression, v_∞ is the terminal velocity of the outflowing gas (km s^{-1}), D the distance to the star (kpc), L_4 the luminosity of the star in units of 10^4 $L_\odot$, $F_\lambda(60)$ the IRAS flux from the star at 60 μm (Jy) and λ_{10} is the average wavelength of the emergent light in units of 10 μm. With the "far" distances given in Table 1, $L_4 = 1$. From the available ground-based and IRAS photometry, we take $\lambda_{10} = 0.2$. Although uncertain, we adopt $v_\infty = 10$ km s^{-1} and we use the measured IRAS fluxes at 60 μm for EU And and V778 Cyg of 0.82 and 1.9 Jy, respectively. With these parameters, we estimate mass loss rates for EU And and V778 Cyg near 10^{-7} $M_\odot$ yr^{-1}, the exact values are given in Table 1.

For a spherically symmetric outflow, we can write for the amount of circumstellar extinction, τ that

$$\tau = \frac{\chi dM/dt}{4\pi R_{in} v_\infty}, \tag{3}$$

where χ is the opacity of the dust (cm^2 gm^{-1}) and R_{in} is the inner radius of the material. Assuming an opacity per gram of gas at 2800 Å of 200 cm^2 gm^{-1} (Jura 1986) and an inner radius where the dust is most concentrated of 10^{14} cm, we derive values for the circumstellar extinction for EU And and V778 Cyg that are listed in Table 1. The derived circumstellar extinctions are somewhat smaller than our estimates for the amount of interstellar extinction. It should be recognized that we are probably overestimating the amount of circumstellar extinction. If the dust grains are formed at 10^{14} cm from the central star, we expect that radiation pressure on the matter would probably produce a value of v_∞ considerably in excess of 10 km s^{-1} (Jura 1984). As can be seen from equation (3), this higher terminal velcoity would lead to a smaller value of τ.

III. OBSERVATIONS

We carried out the observations on 1990 July 25 during one US1 IUE shift. We used the low dispersion echelle spectrograph with the Long Wavelength Prime (LWP) camera and the large aperture setup (Boggess *et al.* 1978).

Our observation procedures followed standard IUE practice. Because the observed stars are variable in brightness, and could possibly have been fainter than V = 13.5 mag at the time of observation, we did not acquire the targets directly with the FES (Fine Error Sensor). Instead, we performed blind offsets from nearby, bright SAO stars and then used finding charts to locate our target star in the field of view. We took one exposure for each star with integration times of 180 and 130 minutes for V778 Cyg and EU And, respectively.

We reduced the data at the Goddard Space Flight Center Remote Data Analysis Facility. We used extracted spectrum disk files which had undergone standard IUE image processing. This image processing includes corrections for geometric distortion due to thermal and local-exposure-level effects, linearization and flatfielding with an Intensity Transfer Function, wavelength calibration using a Pt emission-line calibration image, spectral extraction of the order in question, and absolute flux calibration using a standard star. The resultant echelle-format spectrum is then binned yielding a Merged Extracted LOw (MELO) dispersion disk file. We further reduced the MELO file with the IUESPEC software which used the integration time to convert flux numbers into physical units (ergs cm^{-2} s^{-1} $Å^{-1}$) and adjusts the flux at each wavelength for changes in the instrumental sensitivity as a function of camera header temperature.

With the reduced spectra, we then smoothed the resultant continuum flux with a boxcar filter of 2 pixels in width. We did not detect any signal from either star above the noise level. We have derived continuum-flux upper limits using 150 Å of spectrum centered at 2850 Å and obtained a 1σ value of 5×10^{-16} ergs cm^{-2} s^{-1} $Å^{-1}$ for both EU And and V778 Cyg. In our analysis described below, we use 3σ upper limits for the flux of 1.5×10^{-15} ergs cm^{-2} s^{-1} $Å^{-1}$.

IV. EMISSION FROM THE PHOTOSPHERE OF A MAIN SEQUENCE COMPANION

We first consider the possibility that the carbon-rich stars have main sequence companions. The flux that we detect at the Earth, f_λ, is given by the expression:

$$f_\lambda = \frac{L_\lambda \ \exp(-\tau_\lambda)}{4\pi D^2} \tag{4}$$

where L_λ is the specific luminosity of the star and τ_λ is the sum of the interstellar and circumstellar extinctions. Bohm-Vitense (1981, 1982) has found that the model atmospheres of Kurucz (1979) match well the ultraviolet fluxes from A and F stars. Therefore, to determine the ultraviolet emission from a star, we use Kurucz's models. We set:

$$L_\lambda = 4\pi R_*^2 f_{*,\lambda} \tag{5}$$

where R_* and $f_{*,\lambda}$ are the radius and emergent flux from the star. This latter quantity is primarily a function of the effective temperature of the star.

From the work of Harris, Strand & Worley (1963), we adopt for main sequence stars that:

$$R_*/R_\odot = (M_*/M_\odot)^{0.70} \tag{6}$$

From the same reference, we use the mass-luminosity relationship on the main sequence that:

$$L_*/L_\odot = (M_*/M_\odot)^4 \tag{7}$$

These two expressions result in the following for the effective temperature, T_e:

$$T_{e,*}/T_{e,\odot} = (M_*/M_\odot)^{0.65} \tag{8}$$

With these expressions and the model atmospheres given by Kurucz (1979), we can derive L_{2800} (erg s^{-1} Å^{-1}) the luminosity at 2800 Å. We find for the mass range of interest that:

$$L_{2800} = 8 \times 10^{29} (M_*/M_\odot)^4 \tag{9}$$

With the data for the distances and extinctions given in Table 1, we derive upper limits to the masses for any companions to the carbon stars given in Table 1. The inferred mass is sensitive to the assumed distance and the amount of interstellar extinction. For example, for the "far" distance for V778 Cyg, but with half the extinction given in Table 1, we derive an upper limit for the mass of any main sequence companion of 2.5 $M_\odot$ instead of 6.3 $M_\odot$.

V. EMISSION FROM THE ACCRETION FLOW ONTO A WHITE DWARF

Any companion to a mass-losing red giant can accrete some of the wind material. The binary models that have been proposed require that the companion lie within a few stellar radii of the red giant; therefore, the companion should be accreting ~0.1 of the total mass flowing out in the wind (Jura and Helfand 1984). In the case of a main sequence companion, it is straightforward to show that the accretion-driven luminosity is so low that we would not expect to detect it with our current data. However, if the companion is a white dwarf, so much energy would be released by accretion in the deep gravitational well that it may be possible to detect the resulting ultraviolet emission in our IUE spectra. Specifically, we write for the accretion luminosity, L_{ac} that:

$$L_{ac} = 0.1\ (dM/dt)(GM_{wd}/R_{wd}) \tag{10}$$

where M_{wd} and R_{wd} are the mass and radius of the white dwarf. For a white dwarf of 0.6 $M_\odot$ (Weidemann & Koester 1983) whose radius is 8.7×10^8 cm (Chandrasekhar 1957) and with $dM/dt = 2 \times 10^{-7}\ M_\odot\ yr^{-1}$, this implies $L_{ac} = 30\ L_\odot$. For a star at 1 kpc from the Sun subject to 4 mag of combined interstellar and circumstellar extinction, we would expect a flux at the Earth of $F = 2 \times 10^{-11}$ erg cm^{-2} s^{-1}. While the spectral energy distribution of this emission is not known, we might expect a substantial fraction of the flux to emerge in the ultraviolet in which case we could write that at 2800 Å, $\lambda F_\lambda = F$. Therefore, we might expect that $F_\lambda = 7 \times 10^{-15}$ erg cm^{-2} s^{-1} Å^{-1}, substantially larger than the measured 3σ upper limit to the flux of 1.5×10^{-15} erg cm^{-2} s^{-1} Å^{-1}. Although there are uncertainties, it seems unlikely that there are nearby white dwarf companions to EU And or V778 Cyg if these stars lie at the "near" distance of 1 kpc. However, if these stars lie at the "far" distance, we cannot rule out the possibility of white dwarf companions.

VI. DISCUSSION

Since the typical mass of the main sequence progenitors to most carbon stars is near 1.5 $M_\odot$ (Claussen *et al.* 1987), the upper limits to the masses of any companions to the carbon-rich stars with oxygen-rich envelopes that we place from the IUE results are consistent with the binary star hypothesis for the origin of these systems if the initial main sequence masses of the two stars in the putative binary system are comparable.

Although our data do not rule out the binary models to explain the carbon-rich stars with oxygen-rich circumstellar envelopes, there are other problems with such models. In particular, if there is a disk of oxygen-rich material near the carbon star, it is difficult to understand why as much as 25% of the energy from these systems is processed through the circumstellar disk which both (i) subtends a large solid angle around the carbon star yet (ii) the dust particles are not rapidly driven into the interstellar medium by radiation pressure. Furthermore, the IRAS colors from these stars are similar to those of mass-losing oxygen-rich stars with dust density distributions that fall as r^{-2} (Jura 1986, Zuckerman & Dyck 1986); their far infrared colors do not resemble the typical emission from disks (see, for example, Adams, Lada & Shu 1988).

As noted above, there are severe problems with the current single star "switching" model for the carbon-rich stars with oxygen-rich envelopes. Here, we propose a new single star model for the carbon-rich stars with oxygen-rich envelopes. It has been noted by several authors (see, for example Lambert *et al.* 1990) that the carbon-rich stars with oxygen-rich envelopes are of J-type; they have a high ratio of $^{13}C/^{12}C$. However, there are a number of J-type carbon stars, such as Y CVn which do not display oxygen-rich circumstellar envelopes. This raises the possibility that there are least two sorts of J-type carbon stars. In contrast to the "normal" J type carbon stars which do not display enhanced abundances of s-process elements such as Tc (Utsumi 1985), there is some evidence that the unusual J-type carbon-rich stars with oxygen-rich envelopes do display Tc although not other s-process elements (Maizels *et al.* 1991).

One suggestion for the high value of $^{13}C/^{12}C$ in J-type stars is that they exhibit the products of equilibrium CNO processing. This explanation is not valid for the "normal" J-type stars such as Y CVn, because these stars do not display enhanced nitrogen abundance (Lambert *et al.* 1986) and because their actual ratio of $^{13}C/^{12}C$ may be in excess of the prediction of equilibrium burning (Jura, Kahane & Omont 1988). Here, we hypothesize that the ususual J-type carbon stars with oxygen-rich envelopes do exhibit the products of CNO equilibrium processing. In this case, we expect a high value of $^{13}C/^{12}C$, a high value of [N]/[C] and both carbon and oxygen to have lower than solar abundances. Indirect evidence in support of this hypothesis is that, to date, CO radio emission has not been detected from these stars even though they are reasonably bright in the IRAS 12 μm band (Deguchi, Nakada & Sahai 1990, Maizels *et al.* 1991), although some stars with oxygen-rich circumstellar envelopes can be relatively weak CO sources (Heske *et al.* 1990).

The circumstellar chemistry in the envelopes of carbon stars with a high nitrogen abundance may be very different than the "normal" circumstellar chemistry for carbon stars. As with the "normal" stars, we expect that in their photospheres, CO contains most of the oxygen (Lafont, Lucas & Omont 1982). However, in contrast to the "normal" case, in the photospheres of the carbon stars with high nitrogen abundances the most abundant carbon-bearing molecule after CO probably is HCN rather than C_2H_2 (Tsuji 1964). This difference may be critical in the chemistry. Because the carbon chains in general and C_2H_2 in particular may be the seed species for the formation of solid carbon grains (Keller 1987, Kroto 1988), it may be that solid carbon will not form in the HCN-rich envirornment even though there is excess carbon in the atmosphere. Because SiO may be more abundant than C_2H_2 (Tsuji 1964), it is possible that the solid condensates are oxygen-rich.

There is indirect evidence that C_2H_2 is incorporated into carbon grains in the outflows from carbon-rich stars. As expected theoretically (Lafont, Lucas & Omont 1982), C_2H_2 is observed to be abundant in the outflow from the well studied carbon star IRC+10216 (Keady & Hinkle 1988). In the outer circumstellar envelope of this star, C_2H_2 is photodissociated to produce C_2H (Huggins & Glassgold 1982, Huggins, Glassgold & Morris 1984, Glassgold, Lucas & Omont 1986). The observed amount of C_2H around IRC+10216 is at least a factor of 10 less than that which would predicted if most C_2H_2 is photodissociated to produce this molecule. Instead, it seems that most C_2H_2 is incorporated into solid dust grains. In contrast, there is no evidence that HCN is incorporated into grains.

We predict a large amount of HCN in the circumstellar envelopes of EU And and V778 Cyg. In an Appendix, we discuss how radio observations can be used to place upper limits on the abundance of HCN flowing out of these stars; we argue that currently available data are consistent with high HCN and nitrogen abundances in the outflows from these stars.

It has been proposed that carbon stars with particularly high terminal velocities of the outflowing gas are especially nitrogen-rich (Jura 1991b). There is no evidence that these stars with high terminal velocities have oxygen-rich grains, so that the enhancement of the nitrogen abundance in these "normal" stars may be insufficient to alter their basic carbon grain condensation chemistry.

VII. CONCLUSIONS

We make two main points in this paper.

1. There is no detectable ultraviolet emission from two carbon-rich stars with oxygen rich circumstellar envelopes. Depending upon the interstellar extinctions and distances to these stars, the upper limit to the mass of a main sequence companion is between ~1.5 and ~6 $M_\odot$. If these carbon stars lie at the "near" distance of 1 kpc, it seems unlikely that they have white dwarf companions.

2. We suggest that these stars have oxygen-rich circumstellar envelopes because they are nitrogen-rich and carbon-poor; therefore they have very little C_2H_2, a key seed molecule for the formation of solid carbon. As a result, oxygen-rich solids form.

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APPENDIX: THE HCN OUTFLOW RATE

Above, we suggest that HCN may be abundant in the outflows from the carbon stars with oxygen-rich envelopes. However, Nakada *et al.* (1987) report only upper limits to the J = 1-0 HCN radio emission using the Nobeyama 45m telescope of 0.14 and 0.15 K for V778 Cyg and EU And, respectively. Here, we quantitatively interpret their results.

If we assume $v_\infty = 10$ km s^{-1} and a rectangular emission line profile for both stars, these upper limits to the excitation temperature lead to integrated line widths, W, (K MHz^{-1}) of about 0.9 K MHz^{-1} for both stars. Following the work of Nercessian *et al.* (1989), Jura (1991b) has employed the following to estimate the abundance of HCN in an outflow:

$$\mathrm{W(HCN)} = 9.1 \times 10^{10}\,\frac{\mathrm{dM}}{\mathrm{dt}}\, f\, \exp(-4.26/\mathrm{T}_{ex})\int_0^x \frac{\exp(-y^2)}{v_\infty \mathrm{DBZ}}\,dy$$

where f is the fraction by number of HCN relative to hydrogen nuclei (f = [HCN]/[$2H_2$]), T_{ex} is the excitation temperature of the HCN rotational transition which we take equal to a constant throughout the circumstellar envelope, B is the telescope diameter FWHM (radians) and Z is the partition function of the HCN molecule. We use Z = 0.47 T_{ex} (Morris *et al.* 1987). Also, following Morris *et al.* (1987), we define:

$$x = 2(\ln 2)^{1/2}\mathrm{p}_{max}/\mathrm{BD}$$

where p_{max} is the maximum spatial extent of the HCN emission zone. As discussed by Jura (1991b), the size of the region containing HCN is controlled by photodissociation of this outflowing molecule by the ambient interstellar ultraviolet radiation field. For example, for dM/dt = 10^{-7} $M_\odot$ yr^{-1}, v_∞ = 10 km s^{-1} and the dust to gas ratio given by Jura (1986), we find that $p_{max} = 1.3 \times 10^{15}$ cm. We adopt $B = 1.1 \times 10^{-4}$ corresponding to 22" for the 45m telescope at the HCN frequency (Nakada *et al.* 1987) and $T_{ex} = 75$ K (see Jura 1991b), although this value for the excitation temperature is quite uncertain.

With these parameters, the derived values for f(HCN) are listed in Table 1; they range between 10^{-4} and 10^{-3}. However, because the position assumed by Nakada *et al.* (1987) for EU And may be in error by more than 10" (Maizels *et al.* 1991), the upper limit that we place for f(HCN) for this star may be too low. Also, given all the uncertainties, it is possible that f(HCN) is substantially larger than given in Table 1.

According to the models of Tsuji (1964), in a carbon rich atmosphere, $[HCN]/[N_2]$ is about 0.1, although the abundances used by Tsuji may only roughly correspond to the true abundances in the atmospheres of these stars. Our derived upper limits for the abundance of HCN in the outflows from these stars is consistent with a total nitrogen abundance of 10^{-3} for V778 Cyg and 10^{-2} for EU And.

Table 1

Star	EU And "far D"	EU And "near D"	V778 Cyg "far D"	V778 Cyg "near D"
D(kpc)	2.1	1.0	1.9	1.0
b(°)	-13	...	12	...
|Z| (pc)	470	220	400	210
dM/dt (10^{-7} $M_\odot$ yr^{-1})	1.8	0.81	3.4	1.9
$\tau_{2800,ism}$	4.6	2.2	4.2	2.2
$\tau_{2800,circ}$	1.8	0.8	3.4	1.9
$M_{companion}$ ($M_\odot$)	$\leq$4.9	$\leq$1.5	$\leq$6.3	$\leq$1.9
10^3f(HCN)	$\leq$1	$\leq$1	$\leq$0.2	$\leq$0.2

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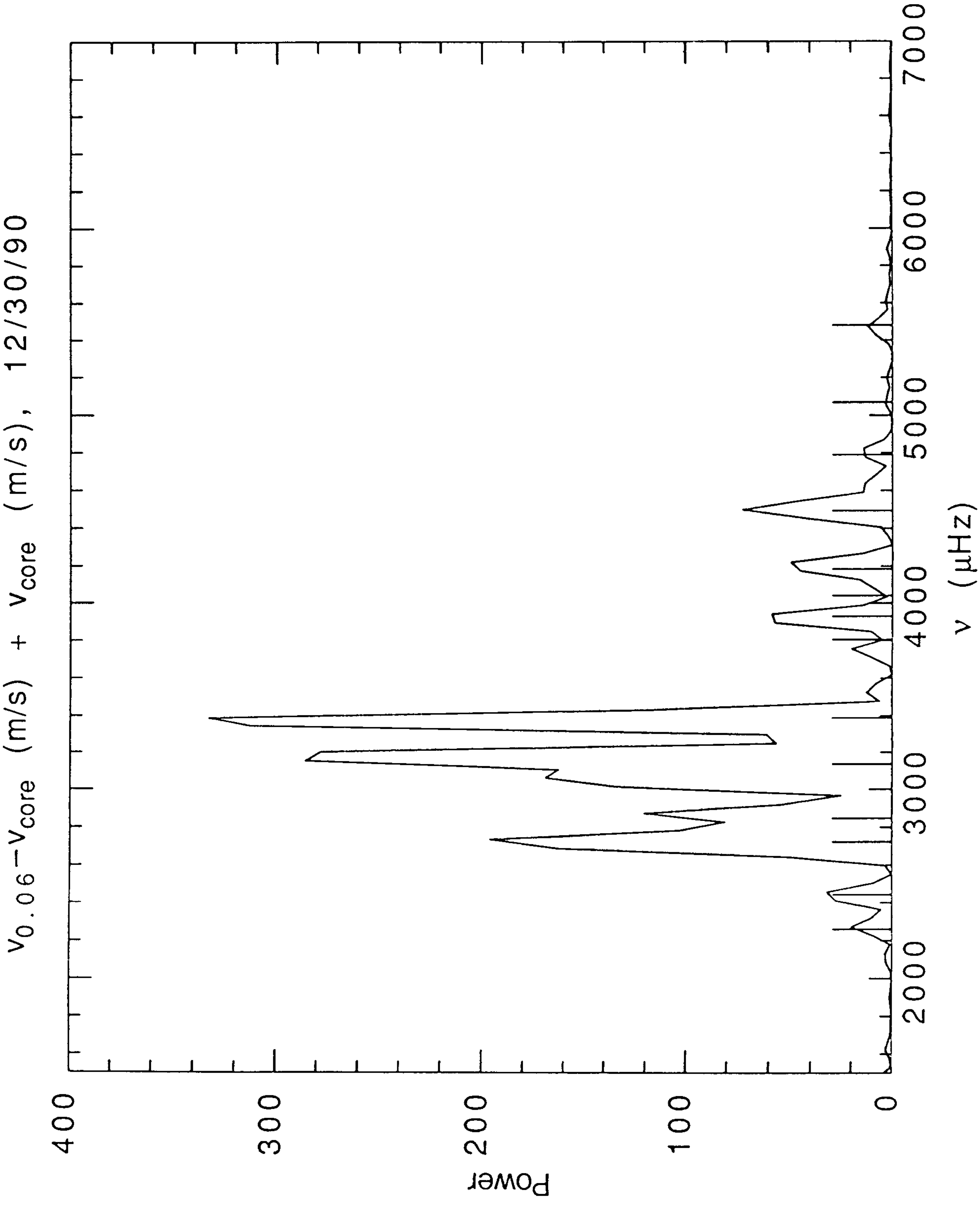
Fig. 1



Michael A. Pura
Isabel Hawkins Fig. 2