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Are a-spherical AGB shells due to a-spherical central stars ?

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Abstract. Drake et al. (1991) observed the carbon star IRC +10 216 with the VLA at 2 cm and determined the FWHM size of the emission region to be 80 x 59 mas with a position angle of 41°. In principle the emission is due to stellar, dust and free-free emission. Based on a detailed dust model that fits the spectral energy distribution and various other constraints it is shown that dust emission at 2 cm is negligible. From a radiative transfer calculation follows that free-free emission is optically thin ($\tau_{\rm 2cm} = 0.03$), and that the FWHM of the brightness distribution should equal the diameter of the central star. The observed size and shape of the 2 cm emission region are therefore interpreted as due to an a-spherical central star. The position angle is in reasonable agreement with that characterizing the circumstellar shell. It is suggested that the a-spherical circumstellar shell observed in IRC +10 216 is due to an a-spherical central star.

Three stars have previously been identified as being a-spherical (o Cet, R Cas and χ Cyg). I discuss the available observations in the literature and conclude that in all three cases there is evidence that the circumstellar shells of these stars are a-spherical as well. These three stars all have binary companions (while none is known for IRC +10 216).

I conclude that non-radial pulsations (NRP), or a (as yet unidentified) binary component which has spun up the central star, are the most likely explanations for the a-sphericity of IRC +10 216. Monitoring the a-sphericity in time should constrain the possible effect of NRP.

Finally, the 0.5-2 cm region is an ideal wavelength region to study the shapes and sizes of (nearby) stars. Even for stars with high mass loss rates, dust emission is relatively small in synthesized apertures $\lesssim 1''$, while free-free emission is also relatively unimportant.

Key words: circumstellar matter – stars: individual: IRC +10 216 – stars: mass loss – stars: AGB, post-AGB

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1. Introduction

The apparently rapid transition from the nearly spherical shells around Asymptotic Giant Branch (AGB) stars to mostly a-spherical Planetary Nebulae (PNe) is one of the most intriguing puzzles in stellar astrophysics.

Observational evidence indicates that most PNe are not spherically symmetric (see e.g. the catalog of Schwarz et al. 1992), while CO maps of most AGB stars show at best moderate departures from spherical symmetry (Bujarrabal & Alcolea 1991, Kahane & Jura 1994, Stanek et al. 1995). Polarimetric data suggests that asymmetry could already be present very early in the transition from AGB to PN phase (Johnson & Jones 1991, Trammell et al. 1994).

Regarding the modeling of the shaping of PNe, the "interacting winds model" (e.g. Kwok et al. 1978, Balick 1987, Mellema 1993) has been very successful in explaining the morphology of PNe. In this model a fast tenuous wind from the central star of the PN interacts with the slow wind from the previous AGB phase. The only condition needed to explain essentially all observed morphologies in PNe is that the AGB wind has some form of axial symmetry. The question is then: what causes the AGB wind to be a-spherical (axial symmetric) and why does it apparently become increasingly so at the end of the AGB phase, or early in the post-AGB phase.

One of the most favored hypothesis in the literature is the influence of a binary companion (Morris 1981, see Livio 1993, 1994 for reviews), either directly though a common envelope phase, or indirectly, by spinning up the AGB star which could make rotation and/or magnetic effects important. What is not explained in these models is why this effect should become important only in the final phase of AGB evolution.

In this *Letter* I present (new) evidence that a-spherical AGB shells may be related to a-spherical central stars. I concentrate on the observed flux in the cm region, and the observed size at 2 cm, of the carbon Mira IRC +10

216. I will model the dust and free-free emission and show that dust emission is negligible at 2 cm, and that free-free emission is optically thin. The implications of a-spherical central stars in the context of the transition from the AGB to the PN phase are discussed.

2. Dust emission

The calculations are performed with the radiative transfer model of Groenewegen (1993, chapter 5), modified to include the calculation of visibility curves (Groenewegen 1996, hereafter G96). This model was developed to handle non-r^{-2} density distributions in spherically symmetric dust shells. It simultaneously solves the radiative transfer equation and the thermal balance equation for the dust in spherical geometry, assuming isotropic scattering.

In G96, the spectral energy distribution up to 3300 μm, visibility curves between 2.2 and 11.3 μm, 2-4 and 8-24 μm spectra, optical sizes and far-infrared sizes of IRC +10 216 are fitted. The model parameters in the best fitting model are: a dust mass loss rate of 8.1 10^{-7} D (kpc) $M_\odot$ yr^{-1} for $r < 123''$ and 7.3 10^{-6} D (kpc) $M_\odot$ yr^{-1} for $r > 123''$, a luminosity at maximum light of 823 10^3 (D (kpc)$)^2$ $L_\odot$, an inner dust radius of r_c = 4.5 $R_\star$, an inner dust temperature of T_c = 1075 K and an effective temperature of $T_{\rm eff}$ = 2000 K. The dust opacity is essentially that of amorphous carbon. The optical constants of Rouleau & Martin (1991) are used, and beyond 1000 μm the opacity is parameterized as $Q_\lambda \sim \lambda^{-0.85}$. The reader is referred to G96 for a discussion on this choice of parameters.

Table 1 lists the available cm observations of IRC +10 216 (column 3). The aperture used in the observations of Drake et al. (1991) is not given and is assumed in the calculations below to be $1''$. Calculations show that the dust emission scales approximately like (aperture)$^{0.76}$ and the precise size of the synthesized aperture is not important. Based on the parameters listed above the SED is calculated taking into account beam effects. The stellar contribution (column 6) is subtracted to get the dust emission (column 7)[1]. Table 1 shows that dust emission is negligible at 2 cm and longer wavelengths. The dust emission is based on the (uncertain) extrapolation of the dust opacity. However, even an unrealistically shallow $Q_\lambda \sim \lambda^{-0.30}$ opacity law would increase the 2 cm dust emission in an $0.4''$ aperture only from 0.01 to 0.07 mJy.

3. Free-free emission

With dust emission being unimportant at 2 cm and beyond, the observed cm fluxes must be due to stellar emission and/or possibly free-free emission. In column 6 the stellar flux is listed for a star with an effective temperature of 2000 K which is the best fitting value derived from fitting the visibility curves (G96). A comparison between the two observations at 2 and 6 cm near maximum light shows that free-free emission must be present as there is a clear excess over what is expected from a photosphere alone.

In G96 (Appendix A) a radiative transfer model is presented to calculate the free-free emission arising in a shell around a star, taking into account optical depth effects. In short, the central star is surrounded by a spherical region out to radius $R_{\rm out}$ where free electrons are present. The H-density is calculated from the gas continuity equation (taking the mass loss rate from the dust model and $v_{\rm gas}$ = 14.5 km s^{-1}). The electron density is calculated by multiplying the hydrogen density with a constant ionisation fraction. The ion density is assumed equal to the electron density. In the present calculations, $R_{\rm out} = 4\ R_\star$ is assumed (the "chromosphere" should always be smaller than the inner dust radius), as well as a constant electron temperature, adopted to be T_0 = 2500 K. In G96 it is shown that the free-free emission is almost independent of T_0 in the range 1600 - 5000 K.

The calculations proceed as follows. The ionisation fraction is fine tuned to get a total flux (stellar + free-free + dust) at 6 cm equal to 0.4 mJy. An ionisation fraction of 7.8 10^{-5} is required (This value is for an assumed distance of 135 pc, and scales like $\sqrt{\rm distance}$). This ionisation fraction is similar to that derived by Spergel (1983; < 4 10^{-5}) and Drake et al. (1991; < 10^{-4}) using much simpler analyses. The stellar + free-free and the total fluxes are listed in columns 8 and 9. The predicted FWHM sizes of the brightness distributions and the free-free optical depths are listed in columns 10 and 11. At 1.5 cm free-free emission is relatively unimportant while at $\gtrsim$3.6 cm it contributes more than 50% of the observed flux. Furthermore, the free-free emission is optically thin. The FWHM sizes are that of the central star, except at 6 cm where $\tau_{\rm ff}$ = 0.3.

The calculations above have been performed for an effective temperature of the central star of 2000 K. From the fitting of the visibility curves the effective temperature was determined to be in the range 1700-2300 K (G96). The cm observations put additional constraints on $T_{\rm eff}$. For example, $T_{\rm eff}$ = 1700 K results in a stellar diameter of 97 mas, which is larger than the observed size at 2 cm of 85 x 59 mas. Inverting the argument, a FWHM < 85 mas implies $T_{\rm eff}$ > 1820 K. Even neglecting dust emission and free-free emission the observed 3σ upper limit on the 2 cm flux close to maximum light of 1.55 mJy implies $T_{\rm eff}$ > 1860 K.

For $T_{\rm eff}$ = 2300 K the stellar diameter is 53 mas while the observed size is 85 x 59, or a mean of 69 mas. For a model with T_0 = 2500 K, the ionisation fraction is determined in such a way as to predict a FWHM at 2 cm of 69 mas, resulting in an ionisation fraction of 1.8 10^{-4}. The predicted fluxes (star + free-free) at 1.5, 2, 3.6 and 6 cm for this model are 3.1, 2.3, 1.4 and 0.81 mJy. Even ne-

[1] The dust optical depth at these wavelengths is very low, e.g. $\tau_{\rm dust}$ = 2.6 10^{-4} at 1.5 cm.

Table 1. Centimeter data on IRC +10 216

Reference	λ (cm)	Flux (mJy)	Aperture ($''$)	Phase	Star[(1)] (mJy)	Dust (mJy)	Star+free-free (mJy)	Total (mJy)	FWHM (mas)	$\tau_{\rm ff}$
Sahai et al. (1989)	1.5	4.1 ± 1.2	90	0.85	2.22	1.76	2.49	4.25	70	0.014
	1.5	6.6 ± 0.4	90	0.30	2.22	1.76	2.49	4.25	70	0.014
	2.0	1.40 ± 0.05	0.4	0.06	1.25	0.012	1.53	1.54	70	0.026
Drake et al. (1991)	2.0	1.16 ± 0.12	?	0.78	1.25	0.032	1.53	1.56	70	0.026
	6.0	0.28 ± 0.05	?	0.78	0.14	0.0017	0.40	0.40	91	0.27
Knapp et al. (1995)	3.6	0.77 ± 0.03	2.8	0.21	0.39	0.015	0.67	0.69	70	0.09
Spergel et al. (1983)	6.0	0.42 ± 0.10	4.5	0.03	0.14	0.0050	0.40	0.41	91	0.27

(1) Flux of the stellar photosphere for $T_{\rm eff}$ = 2000 K. For the wavelength region of interest it is given by S_ν (Jy) = 2.00 $(2000/T_{\rm eff})^3$ $(500\mu{\rm m}/\lambda)^2$. This shows the largest uncertainty is the effective temperature. The uncertainty in the scaling factor is related to the error in L/D^2 (the total observed flux) which is known to within 5%. The angular diameter of the star is given by 70.2 $(2000/T_{\rm eff})^2$ mas.

glecting dust emission these values are much higher than observed, except at 1.5 cm, and can be excluded.

Given the fact that the model with $T_{\rm eff}$ = 2000 K predicts fluxes and a size at 2 cm in excellent agreement with observations, the cm observations limit the value of $T_{\rm eff}$ to 2000 ± 50 K.

4. Discussion

It was shown that dust emission at 2 cm is negligible, that free-free emission at 2 cm is optically thin and that therefore the FWHM size of the 2 cm emission region should equal the diameter of the central star. Drake et al. (1991) determined the size of the 2 cm emission region to be 80 x 59 mas, with a position angle of 41°. Although they warn that "atmospheric phase errors at 2 cm can easily cause intrinsic unresolved sources to look slightly extended in [VLA] A array observations", they also mention that if the deconvolved source size is the real one, the inferred brightness temperature is 1920 K which is very close to the best fitting value of 2000 K for the effective temperature. This probably means that the a-sphericity observed in IRC +10 216 is real, and hence that the central star is a-spherical. Additional evidence that their result is no artifact is that the position angle determined by Drake et al. is in reasonable agreement with that characterizing the circumstellar envelope, as determined by Lucas et al. 1995 (PA = 20° from $\sim$ 3$''$ resolution maps of CN, SiC_2 and SiS), Guélin et al. 1993 (MgNC, C_4H), Kastner & Weintraub 1994 ($\sim$20° from J and H images of the reflection nebula), Bieging & Tafalla 1993 (HC_3N, C_3N, SiS). This strongly suggests that the a-spherical circumstellar shell observed in IRC +10 216 is due to the a-spherical central star.

Other stars have been suggested to be a-spherical. Haniff et al. (1995) mention that differences between the major and minor axis of up to 30% occurred at certain epochs for the Mira variables *o* Cet, χ Cyg and R Cas as derived from optical visibility observations. If a-spherical stars triggers a-spherical shells then the shells around these three stars should be a-spherical as well.

The a-sphericity of *o* Cet is well known (Karovska et al. 1991, Wilson et al. 1992, Haniff et al. 1992, Quirrenbach et al. 1992). The axial ratio of the star is about 0.85 and most authors find a position angle of about 120° although it may also vary with phase. Regarding the circumstellar shell, Planesas et al. (1990) find in their CO maps a bipolar structure. Stanek et al. (1995) confirm this result. *o* Cet is therefore another a-spherical star surrounded by an a-spherical shell, although it is not clear whether the position angles are similar.

For χ Cyg there is not much information on the circumstellar shell. Bujarrabal & Alcolea (1991) present CO J=1-0, 2-1 and ^{28}SiO and ^{29}SiO J=2-1 (v=0) maps and write they are "roughly spherical", although I would interpret the maps as showing deviations from spherical symmetry (with an estimated axial ratio of 0.72-0.88). Stanek et al. (1995) map the CO(3-2) transition and find an axial ratio of 0.67 with a PA of 115°.

Concerning R Cas, Tuthill et al. (1994) show that it is elongated in the N-S direction with an axial ratio larger than that in *o* Cet. Chapman et al. (1994) note that there is a separation of maser groups that suggest that they may be confined to an axially symmetric structure. Lucas et al. (1992) and Bujarrabal & Alcolea (1991) present SiO and CO maps and mention that they are roughly spherical. Stanek et al. (1995) find an axial ratio of 0.77 with a PA of 70° in their CO(3-2) map.

In summary, for *o* Cet, χ Cyg and R Cas there is evidence that the circumstellar shells are non-spherical, and this may be related to the a-spherical central stars.

If AGB stars for some reason become more a-spherical as they ascend the AGB, this could explain the apparently rapid transition from mostly spherical AGB winds to mostly a-spherical Planetary Nebulae. A-spherical stars will in all likelihood lead to a-spherical mass loss which is required in the "interacting winds model".

Livio (1993, 1994) discusses some mechanisms which can lead to a density contrast in the AGB wind: (a) common envelope (CE) evolution, (b) magnetic fields and (c) rotation.

That CE evolution does play a role in at least some cases is evident from the presence of PNe with close binary companions (Livio). On the other hand, only a small fraction (17-22%) of binaries has close enough companions to go through a CE phase (see Livio 1993, 1994 for a discussion and references), while about 80% of PNe are a-spherical (Mellema 1993, chapter 1).

Livio concludes that magnetic fields and rotation do not play a role in single AGB stars, but can become important when the AGB star is spun up, either through CE evolution or by a companion. Even a low-mass object like a brown dwarf or a planet can spin up the AGB star to 35% of the break-up velocity, sufficient to create a compressed equatorial outflow.

What about non-radial pulsations (NRP)? NRP have been suggested to explain some spectroscopic and photometric observations for o Cet (Shawl 1974). Soaker & Harpaz (1992) investigate the role of NRP and concluded that non radial p modes may become important when the envelope mass drops below $\sim$0.1 $M_{\odot}$. This is consistent with the apparently sharp increase of the a-sphericity at the end of the AGB. With a mass loss rate of 10^{-4} $M_{\odot}$ yr^{-1} at the tip of the AGB the a-sphericity would develop over the last 1000 years of a stars' life on the AGB. Soaker & Harpaz claim that in order for non-radial modes to be important it is necessary "to have some mechanism that will define a symmetry axis". They recognize that rotation or a magnetic field defines such an axis but claim this is not sufficient. Their final conclusion is that non-radial modes are only important when the AGB star is spun up by a binary companion.

What about the binary nature? o Cet, χ Cyg and R Cas all have binary companions. None is known for IRC +10 216. The companion of o Cet is located at a separation of about 0.61$''$ at a position angle of about 111°. (Karovska et al. 1993). Interestingly, but possibly a mere coincidence, the PA of the binary companion and that of the major-axis of the star are the same within 10°. One would expect the PA's to be the same if the orbital plane is perpendicular to the rotation axis.

The companion to R Cas is located at 27.8$''$ at a position angle of 331° (Proust et al. 1981), while the companion to χ Cyg is located at 159$''$ at a position angle of 254° (Proust et al. 1981). For R Cas the PA of the binary and of the major axis are the same within 30°.

The fact that three stars that are a-spherical have binary companions leads to the speculation that IRC +10 216 may also have one.

5. Concluding remarks

The result of the modeling of the centimeter observations of IRC +10 216 suggest that the central star is a-spherical. It is not possible to identify the cause of the a-sphericity. Non-radial pulsations are a possibility which require further study. Alternatively, rotation can be important *if* IRC +10 216 has a binary companion.

In the near future new optical visibility data will become available to study the a-sphericities in more stars (and the time variability of the visibilities, to constrain the effect of NRP). One disadvantage of optical visibility studies is the possible influence of scattering and the plenitude of spectral lines, so that it is difficult to get a determination of the radius in the continuum.

The results presented in Sects. 2 and 3 suggest that it may be worthwhile to observe (and monitor) AGB stars at cm wavelengths. This method allows one to study the central stars of objects with high mass loss rates as well, which is essentially impossible using optical and NIR visibilities since these are very sensitive to dust emission. The optimum wavelength to study the central stars is 0.5-2.0 cm. In the case of IRC +10 216 and adopting a synthesized aperture of 1$''$ the central star contributes 80-90% of the total flux. At longer wavelengths free-free emission, while at shorter wavelengths dust and molecular line emission become important.

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