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Letter to the Editor

Resolution of a fossil dust shell around U Hydrae using maximum entropy image reconstruction

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Abstract. High resolution image reconstruction techniques applied to the 60 and 100 μm data obtained with the InfraRed Astronomical Satellite reveal the presence of a detached ring of dust around the evolved carbon-rich star U Hydrae. The ring is clearly resolved at 60 μm but only marginally at 100 μm. The 60 μm image provides the first direct evidence that the far-IR excess associated with cool carbon stars is due to a previous episode of high mass loss. The age of the fossil shell is estimated at 12,000 yrs and the mass loss rate at 5 10^{-6} $M_\odot$ yr^{-1}. This is about a factor 25 higher than the present-day mass loss rate. It is concluded that the mass loss rate of carbon stars on the Asymptotic Giant Branch is variable on a timescale that is compatible with the thermal pulse timescale of intermediate mass stars in that evolutionary phase.

The Groningen IRAS data reduction system runs within GIPSY and is available to outside users.

Key words: Techniques: image processing; Stars: AGB - evolution - mass–loss; Infrared: stars

1. Introduction

Stars on the Asymptotic Giant Branch (AGB) are evolved low or intermediate mass objects with initial mass on the main sequence between 0.8 and 8 $M_\odot$ that are burning H and He in layers near a degenerate C/O core. They are characterized by very large mass loss rates (10^{-7} to 10^{-4} $M_\odot$ yr^{-1}) via a slow and dusty stellar wind with expansion velocities typically between 5 and 30 km s^{-1}. These high mass loss rates in fact determine the evolution of stars in this phase. The growth of the stellar core due to nuclear burning processes, which usually determines the course of events in stellar evolution, occurs at a rate which is several orders of magnitude smaller than the surface mass loss via the stellar wind (e.g. Schönberner 1983). Therefore knowledge of the AGB mass loss rate as a function of time is necessary in order to understand stellar evolution on the AGB.

Most of our current understanding of AGB mass loss stems from observations of the circumstellar envelope these stars possess, and in particular of the dust in the ejecta. The IRAS data have shown that oxygen-rich AGB stars form a sequence of increasing redness in the IRAS colours which is interpreted as a sequence of increasing mass loss rate (van der Veen & Habing 1988). The carbon-rich stars however show much more scatter in the IRAS colours, and a significant fraction has a large 60 and 100 μm excess (Willems & de Jong 1988). For a definition of the 60 and 100 μm excess we refer to Zijlstra et al. (1992). This excess is interpreted as caused by the remnant of a previous phase of higher mass loss, implying that the mass loss rate for carbon stars is not constant in time but varies considerably. Recently a re-analysis of the IRAS data for a large sample of oxygen-rich and carbon-rich stars has shown that in fact all AGB stars, irrespective of their chemical composition, can show a 60 and 100 μm excess, but that only a small fraction of the oxygen-rich stars show the effect (Zijlstra et al. 1992).

The interpretation of the variations of the mass loss is not clear, but it is possible that thermal pulses are responsible. These occur when the He-layer near the core of the star suddenly ignites and injects an enormous amount of energy in the atmosphere, temporarily quenching the energy production in the H-burning layer. Model calculations show (E.Vassiliadis and P.R. Wood, 1993 ApJ *in press*) that thermal pulses change the surface gravity and luminosity of the star considerably, which will almost certainly have an effect on the mass loss rate. In order to test a possible connection between thermal pulses and mass loss it is necessary to obtain information on the timescale of the mass loss variations, that can be compared to the timescales of thermal pulses (typically 10^4 to 10^5 yrs (Boothroyd & Sackmann 1988a).

The time that has elapsed since the phase of high mass loss usually is derived from the IRAS broad-band photometry by using a dust model, which introduces uncertainties because the dust grain properties and the geometry are not (well) known. A direct measurement of the inner radius of the detached envelope would give a much more accurate measurement of the age

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of the shell and also of the mass loss rate in the shell (although here dust grain properties enter again), and it gives insight in the geometry of the wind. In only one case the detached envelope around a C-star (S Sct) was mapped in CO(1-0) (Olofsson et al. 1992) and showed a ring of molecular gas more or less homogeneously distributed, allowing a measurement of the age of the shell. However the CO in detached envelopes is prone to photo-dissociation and the observed distribution of CO may not reflect the distribution of the gas and dust accurately. When the shell is older than 10^4 years, the CO will probably be completely photo-dissociated and the detached shell is only detectable in the far-IR. Examples of extended emission around AGB and other stars have been reported before in the literature (e.g. Gillett et al. 1986; Hawkins 1990) but they are mostly based on the low resolution co-added IRAS images. A recent study of Young et al. (1993) of one-dimensional co-adds of the 60 and 100 μm IRAS scans of a large sample of AGB stars shows that many objects have faint extended emission, from which their mass loss history can be derived.

We have applied maximum entropy image reconstruction techniques (HIRAS) (Bontekoe, Koper, and Kester, in preparation; Gull 1989; Skilling 1989) to the IRAS 60 and 100 μm observations of a sample of AGB stars in order to derive information about the spatial distribution of the excess emission. These techniques allow a spatial resolution approaching the nominal diffraction limit of the telescope, which is 1 arcmin at 60 μm and 1.7 arcmin at 100 μm (indicated as the circles in Figs. 1 to 3). In this *Letter* we report the discovery of a detached envelope around the C star U Hydrae, which unambiguously demonstrates that the 60 and 100 μm excess in C stars is due to a previous phase of high mass loss.

2. Maximum Entropy image reconstruction of IRAS data

The unprocessed IRAS data contain information at higher resolutions than presented in e.g. the co-added maps (CoAdds) of the IRAS Sky Survey Atlas (ISSA 1991), because of the layout of the focal plane and the sampling density. The combination of this higher intrinsic resolution and the multi coverage observing strategy allows for the construction of high resolution images (Bontekoe et al. 1991, Aumann et al. 1990). The results presented here are obtained by applying MemSys5, the maximum entropy (MaxEnt) software package (Gull & Skilling 1991). The astrophysical importance of our results goes beyond the significant increase in angular resolution by a factor of ~ 5 over CoAdds. The high-resolution IRAS images now can be compared directly with results obtained with instruments having similar resolutions.

Until recently, MaxEnt methods were ill-equipped to handle images containing both sharp and extended structure. In a typical astronomical image many different scale lengths are present. The development of a 'multi-channel' MaxEnt image reconstruction method (Weir 1992) has made it possible to treat multiple scale lengths in one image. This technique has been extended to PME (Pyramid Maximum Entropy), because the results from straightforward application of these multi-channel techniques to IRAS images were regarded unsatisfactory (Bontekoe, Koper & Kester, in prep).

With the use of 'pyramid' images, spatial correlations with many scale lengths can be properly reconstructed in the image. Pyramid images are an extension of multi-channel reconstruction techniques and appear particularly suited for the treatment of IRAS data. In a pyramid image the channels have different pixel sizes; e.g. a 64x64 pixel image is the sum of a 64x64, a 32x32,..., a 2x2, and a 1x1 pixel channel, all covering the same image area. Each channel acts as a band pass filter, matched for spatial frequencies increasing by factors of two. Point sources are reconstructed in a channel with smaller pixels; broad structure in a channel with larger pixels. In contrast to 'conventional' multi-channel methods, PME requires relatively little extra computing power over single-channel techniques.

3. IRAS high resolution images of R For and U Hydrae

Here we present the results obtained by applying this new method to the IRAS 60 and 100 μm data of U Hydrae. U Hya is a Srb type variable (Kukarkin et al. 1969) and shows enhanced abundance of Technetium (Little-Marenin & Little 1979) indicating that the star has experienced the third dredge-up, and providing direct proof that thermal pulses have occurred. CO millimeter detections were reported by Zuckerman & Dyck (1986), Olofsson et al. (1988) and Nyman et al. (1992). The CO expansion velocity found in these studies is between 7.9 and 10.7 km s^{-1}. The profiles do not show evidence for the presence of a detached envelope as in the case of S Sct. This lack of extended CO emission could be due to the fact that the CO in the detached shell has already been dissociated, or the expansion velocity of the detached shell and that of the present-day mass loss are similar, resulting in a blend of the two components. The star is associated with a source in the IRAS Small Scale Structure Catalogue (SSSC).

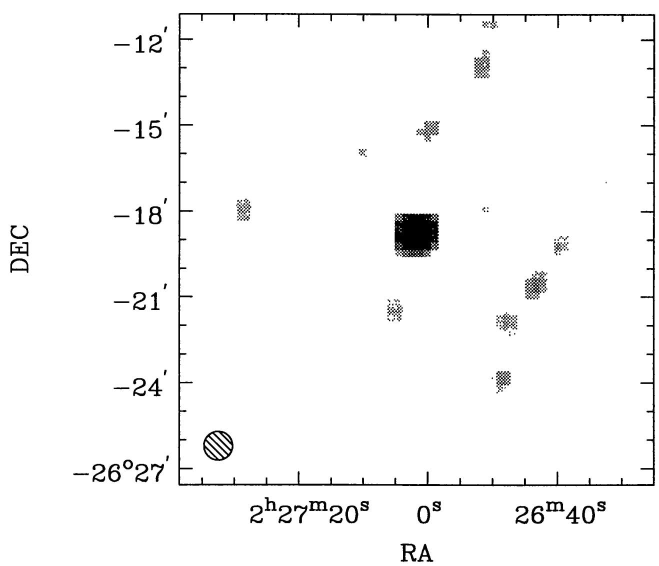

Fig. 1. Grey-scale image of the maximum entropy solution to the 60 μm brightness distribution of R For. Dimension of the image is 16x16 arcmin and the pixel size is 15 arcsec. The object is expected to be a point source.

Before discussing the results for U Hya, it is useful to show the 60 μm image of the carbon star R For. This object has no excess at 60 and 100 μm (Loup 1991) and is not associated with extended emission. Furthermore the surroundings of

R For are relatively free of cirrus emission at 60 μm. The 60 μm flux quoted for R For in the IRAS Point Source Catalogue is 16.0 Jy which is close to the value of 17.2 Jy given for U Hya. Therefore the only difference between R For and U Hya is the fact that the latter is associated with a small extended source. In Figure 1 we show the 60 μm image of R For, which essentially shows a point source as expected.

Figures 2 and 3 show grey-scale image of the solution to the 60 and 100 μm IRAS survey data respectively. At 60 μm the object is resolved into a central point source and a detached ring at a mean distance of 1.75 $\pm$ 0.5 arcmin whose thickness is not resolved. At 100 μm the spatial resolution is not sufficient to resolve the object into a central source and ring, but the distribution of intensities is consistent with the 60 μm result. The total diameter of the ring is 3.50 arcmin at 60 μm. In both images the right part of the ring is brighter than the left part, which may suggest that the material is not distributed evenly in the detached envelope. Both images appear slightly boxy, which may be caused by the amplification of small imperfections in the calibration of the data, which is inherent to any image restoration method. The total flux of central source plus ring at 60 μm is 41 $\pm$ 8 Jy, and of the central source 18 $\pm$ 3.5 Jy.

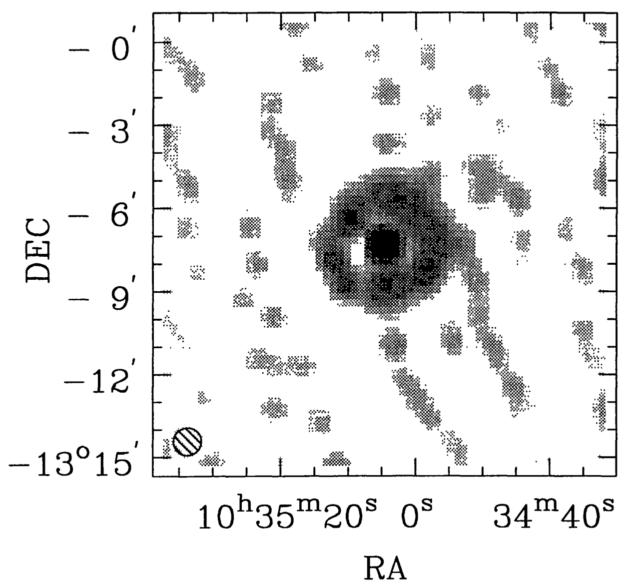

Fig. 2. Grey-scale image of the maximum entropy solution to the 60 μm brightness distribution of U Hya observed during the IRAS survey. Dimension of the image is 16x16 arcmin and the pixel size is 15 arcsec

It is likely that the radius of the ring measured from the 60 μm image is the inner radius of the dust shell. For any reasonable choice of the density distribution of dust grains in the detached shell the dust seen at 60 μm is the hottest dust in the shell, i.e. is near the inner radius. From a simple optically thin dust model (see below) we derive a dust temperature at the inner radius of the detached shell of 50 K. This implies that heating from the diffuse interstellar radiation field can be neglected. Such a distribution of dust, when spatially resolved, will show a very thin ring-like structure projected against the sky when observed at 60 μm because the dust temperature in the shell decreases outwards rapidly and cold dust at large distance from the star will not contribute at 60 μm. Therefore the 60 μm image cannot be used to derive information on the outer radius of the shell, and what we see in Figure 2 is the inner radius of the detached dust shell.

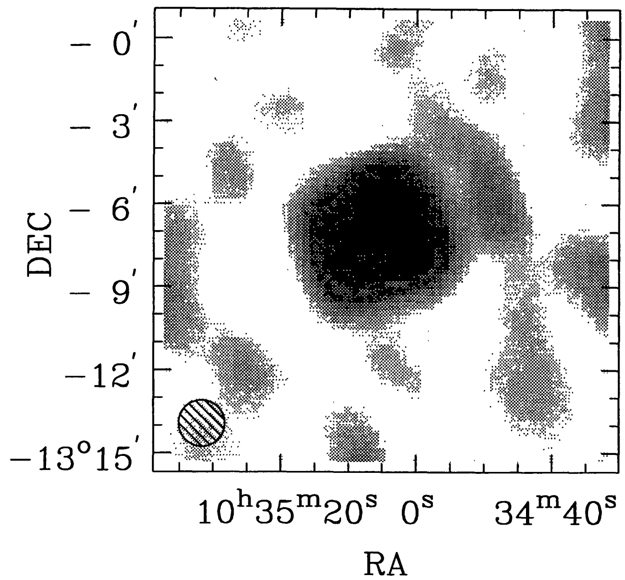

Fig. 3. Same as Figure 2 but for 100 μm

4. discussion

In order to derive an age for the shell, the distance to U Hydrae and the expansion velocity of the shell must be known. Unfortunately no good distance measurement is available in the literature, and we adopt a bolometric luminosity of 10^4 $L_\odot$. When combined with the observed energy distribution (van der Veen & Rugers 1989) we obtain a distance of 350 pc. This proximity of U Hydrae to the Earth is probably the reason why the detached envelope could be resolved. No measurement of the expansion velocity in the shell is available. The millimeter emission from the CO molecule which is observed (Kastner 1990) reflects a new phase of (much lower) mass loss. The measured expansion velocity of 8 km s^{-1} is probably an underestimate of the expansion velocity of the detached shell because the mass loss rate in the detached shell (see below) is significantly higher and mass loss and outflow velocity are correlated in AGB stars (Wood 1990). Significant differences in expansion velocity of the old and new mass loss were found in S Sct (Olofsson et al. 1992). We adopt an expansion velocity of 15 km s^{-1}. Finally we find an age for the dust shell of 12,000 yrs.

The size of the detached shell, the inner radius R_i and the total flux measured at 60 μm allow an estimate of the dust mass loss rate in the shell. Since the dust is optically thin we use a simple spherically symmetric optically thin dust model (Sopka et al. 1985), and a central star which we assume to be a black body of 2,000 K and with a luminosity of 10^4 $L_\odot$. We use a dust emissivity law for C-rich dust $Q(\lambda) = Q_0(\lambda/\lambda_0)^{-\beta}$ with $\lambda_0 = 1.0$ μm, and a density law $n(r) = N_i(R_i/r)^\alpha$. Note that we do not have enough constraints to determine α and β, in particular we cannot use the 100 μm flux coming from the detached shell as the source is not completely resolved at 100 μm. We then have to make an assumption about the values of α and β. In the calculation we take into account the spectral transmission of the 60 μm filter.

A difficulty in estimating the mass loss rate in the detached shell is the uncertain value of the outer radius of the dust shell. We adopt a thickness of the shell of 1 arcmin, which is equal to the spatial resolution at 60 μm. A thickness of 1 arcmin implies that the high mass loss phase lasted 6700 yrs (using a distance of 350 pc). Our calculations indicate that for larger shell thickness the resulting mass loss rate changes by at most a factor 2. In the case of a thinner shell than adopted here the mass loss rate is underestimated. Similar effects were also noted by Groenewegen & de Jong (1993, submitted to A&A) in their analysis of the energy distribution of S Sct.

The dust mass loss rate in the shell can be written as:

$$\dot{M}_{\rm dust}(R_i) = \dot{M}_0(R_i) \left(\frac{d}{350}\right)^2 \left(\frac{1}{Q(1\ \mu m)}\right) \left(\frac{V_e}{15}\right) \quad (1)$$

where d is the distance in pc, V_e is the expansion velocity in km s^{-1}. For $3 \geq \alpha \geq 1$ and $1.5 \geq \beta \geq 1.0$, we find $\dot{M}_0(R_i) = 2.35\ 10^{-8}$ ($\pm$ 35 %) $M_\odot$ yr^{-1} which, with a gas-to-dust ratio of 200 (Jura 1986) corresponds to a total mass loss rate of 4.7 10^{-6} $M_\odot$ yr^{-1}. The present-day mass loss rate is estimated to be 2 10^{-7} $M_\odot$ yr^{-1} (Kastner 1990), which means that the mass loss variation is a factor 25.

It is interesting to compare the age of the shell to inter-pulse timescales, t_{ip}, of AGB stars. The core-mass-interpulse period for solar metallicity stars is given by (Boothroyd & Sackmann 1988a) log $t_{ip} = 4.5(1.689-M_c)$ where M_c is the core mass in $M_\odot$. Carbon stars are thought to be near the end of their AGB evolution and the core mass for a 10^4 $L_\odot$ star based on the core-mass-luminosity relation (Boothroyd & Sackmann 1988b) is 0.65 $M_\odot$ which corresponds to an interpulse period of 47,000 yrs. For a 13,000 $L_\odot$ star the interpulse period is 28,000 yrs. Given the uncertainty in the luminosity we may conclude that the age of the shell around U Hydrae is a significant fraction of the inter-pulse period for evolved AGB stars. We have found several cases which have more evolved dust shells (Loup, Waters, Kester and Bontekoe, in preparation) and we conclude that the timescale for variations in the mass loss in carbon stars is compatible with the inter-pulse period which follows from evolutionary calculations.

The examples shown in this *Letter* illustrate the potential of our new image reconstruction techniques, and open new ways of looking at IRAS data. We expect that the high resolution images will be of value in preparing for the ISO mission. The high resolution image reconstruction routines are now implemented in the Groningen Image Processing SYstem GIPSY, and are open to outside users. Those interested can contact Dr. Paul Wesselius at SRON Groningen (email address paul@sron.rug.nl).

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