Article:
Wareing, CJ (2008) Wonderful Mira. Philosophical Transactions A: Mathematical, Physical and Engineering Sciences, 366 (1884). 4429 - 4440. ISSN 1364-503X

https://doi.org/10.1098/rsta.2008.0167

Wonderful Mira

By Christopher John Wareing

Department of Applied Mathematics, University of Leeds, Woodhouse Lane, Leeds LS2 9JT, UK; cjw@maths.leeds.ac.uk

Since being named 'wonderful' in the 17th century for its peculiar brightness variability, Mira A has been the subject of extensive research and become the prototype for a whole class of 'Mira' variable stars. The primary star in a binary system, Mira A is reaching the end of its life and currently undergoing an extended period of enhanced mass-loss. Recent observations have revealed a surrounding arc-like structure and a stream of material stretching 12 light years away in opposition to the arc. In this article, I review recent model ling of this cometary appearance as a bow shock with an accompanying tail of material ram-pressure-stripped from the head of the bow shock, place Mira in an evolutionary context, predict its future with reference to the similar star R Hya and planetary nebula Sh 2-188 and speculate some avenues of research both on Mira itself and other 'Mira-like' stars with bow shocks and tails. I also discuss the implications of this discovery for our own star, the Sun.

Keywords: Hydrodynamics – stars: individual (Mira) – stars: AGB and post-AGB – circumstellar matter – ISM: bubble – stars: mass-loss

1. Four centuries of observing Mira

In 1596, an amateur astronomer by the name of David Fabricius (1564 - 1617) noted a long-period variable star, later called o (omicron) Ceti by Bayer (1603) Whilst using the star to determine the position of a planet Fabricius thought to be Mercury, he noted that it increased in brightness from magnitude 3 on August 3 to magnitude 2 on August 21 (Fabricius 1605). In September it had faded and by October it had vanished entirely. With such characteristics, Fabricius implied the star was a nova, but on February 15 1609, he observed that it had reappeared. Then practically forgotten, it was not until 1638 that Johann Fokkens Holwarda (1618 - 1651) rediscovered the star and determined its period to be 333 days, impressively close to the modern period determination of 332 days. In 1642, Johannes Hevelius of Danzig (1611 - 1687) gave the star its now familiar name of Mira, 'the wonderful', in his work *Prodomus Astronomiae*. Mira also fulfils the basic requirements to be the Star of Bethlehem, meaning the Gospel of Matthew may contain the earliest observation of the star (Sigismondi 2002).

Mira is now known to be the brighter star (Mira A) in a binary system and is the prototype for the class of 'Mira' variables: pulsating variable stars with very red colours and pulsation periods longer than 100 days. Reaching the end of its life, Mira has evolved off the Main Sequence and along the red giant branch. It is currently evolving along the asymptotic giant branch (AGB) on route to becoming a white dwarf before fading to obscurity. On the AGB, the star is losing mass via a relatively slow wind (~ 10 km s^{-1}) which carries away between 10^{-7} and 10^{-6} solar masses of material per year. In the next phase of evolution, the post-AGB phase, the white dwarf will eject a fast ($\sim$ 1000 km s^{-1}), tenuous wind which will sweep up the circumstellar AGB material and illuminate the resulting shell, a planetary nebula (PN). Our Sun, having a similar mass to Mira A, will eventually undergo the same process. The second star in the binary system, Mira B, is accreting some of the ejected AGB material, but the orbital distance is so large that only a small fraction of the ejected AGB wind material is accreted. Mira B is usually classed as a white dwarf, but this is now somewhat controversial (Karovska et al. 2005; Ireland et al. 2007). What can be inferred is that any stellar wind from Mira B, whilst potentially fast, is most likely to be insignificant in mass flux and energy terms when compared to that of Mira A and unlikely to illuminate the surrounding structure owing to the small extent of the ionized zone around it (Matthews & Karovska 2006).

During routine inspection of incoming UV images taken with the Galaxy Evolution Explorer satellite (GALEX), Martin et al. (2007) discovered a nebulosity near the location of Mira. Deeper observations revealed an arc-like feature to the South and a stream of material stretching northward of the location of Mira, extending over a total length of two degrees on the sky. Using the revised Hipparcos-based distance (Knapp et al. 2003) to Mira of 349 light years, Martin et al. estimated the spatial extent of the tail to be approximately 12 light years, over three times the distance between our Sun and the nearest star. In interpreting the origins of the wonderful cometary structure, Martin et al. compared its alignment to the spatial motion of the Mira system. They found that the direction of the space velocity of 130 km s^{-1} was consistent with the head of the arc-like structure and postulated that the feature is a bow shock caused by motion through the interstellar medium (ISM). The nebulosity in the North is a tail of material ram-pressure stripped from the head of the bow shock. A mosaic of the deeper UV observations is reproduced in figure 1.

Martin et al. estimated the age of the tail to be 30,000 years, based on the time taken for Mira to travel the length of the tail and inferred that features in the tail provide an unprecedented record of Mira's wind-ISM interaction over that period. They suggested that the density variations along the tail reflect changes in the mass-loss rate, in particular reflecting short periods of enhanced mass-loss a star goes through three or four times at the end of AGB phase of evolution, known as thermal pulsing events (Vassiliadis & Wood 1993). Their search for counterparts at other wavelengths revealed only the knots behind the bow shock show Hα emission, with optical spectroscopy providing evidence that they have been shocked and ionized by the post-bow shock flow.

Finally, Martin et al. consider in some depth the mechanism of the far UV emission observed from the tail. Ruling out dust scattered emission and ambient interstellar radiation, they propose that the emission is excited collisionally by the interaction of H_2 in the cool wake with hot electrons in the post-shock gas resulting from the bow shock which also entrains and deccelerates the wind. This they find consistent with the estimated age of the tail of 30,000 years.

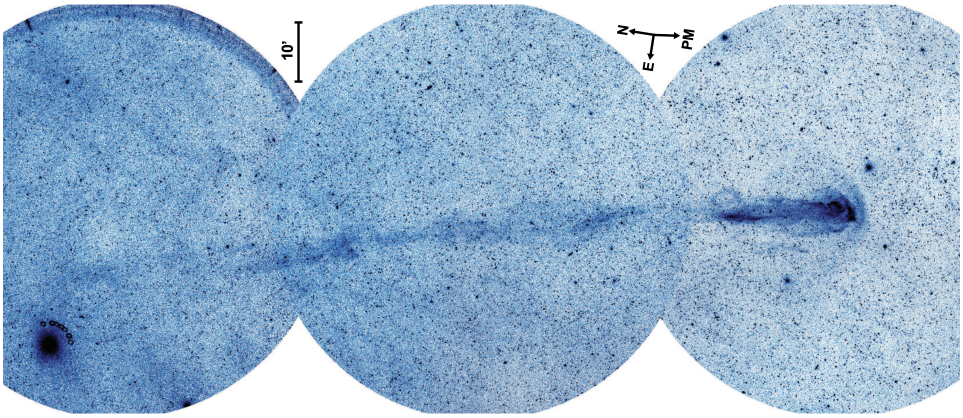

Figure 1. The mosaic'd UV images of the cometary structure surrounding the Mira system taken with GALEX. Note the consistency of the proper motion (PM) with the head of the bow shock. This figure is a reproduction from Wareing et al. (2007c), which is a version of the original observation published by Martin et al. (2007). Please consult these references for full details.

(*a*) *A bow-shock around another AGB star: R Hydrae*

This is not the first case of an arc-like structure around an AGB star or of such structure being interpreted as a bow shock. Observations taken using the Multiband Imaging Spectrometer for Spitzer (MIPS) on-board the Spitzer Space Telescope in 2006 revealed a one-sided parabolic arc to the west of the Mira variable star R Hydrae (R Hya), stretching from north to south (Ueta et al. 2006) and modelled as a bow shock by the author (Wareing et al. 2006b). At 50 $\mathrm{km\,s^{-1}}$, R Hya is moving ~ 2.5 times slower than Mira through the ISM and the bow shock is much smaller, according to the ram pressure balance – only a quarter of a light year ahead of the star and three-quarters of a light year wide across the star. There are some indications of material downstream of R Hya, in particular a number of knots downstream of the star, but no clear evidence for a tail of ram-pressure-stripped material. The period of R Hya also seems to have evolved significantly over 300 years, compared to the stability of Mira's period, which may relate to the difference.

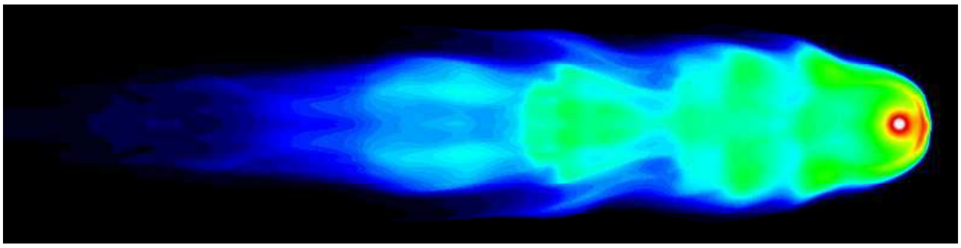

Figure 2. A snapshot of the density datacube, collapsed along a line of sight perpendicular to the direction of motion, 450,000 years into the AGB evolution. The snapshot is 4 x 16 light years. This figure reproduces part of figure 1 from Wareing et al.(2007c).

2. A bow shock and tail model of Mira

Seeing the parallels between R Hya and Mira, the author developed a model tuned to the parameters of Mira and performed hydrodynamic simulations following the AGB phase of evolution (Wareing et al. 2007c). The aim of the simulations was to fit the position of the bow shock ahead of Mira A, the width of the bow shock across the position of Mira A, the undulating density profile along the tail (naively assuming direct relationship between emission and material density), the length and width of the tail and the presence of the ring-like structure in the tail one third the way downstream from the star.

Figure 2 shows a snapshot of density from the three-dimensional simulation of Mira collapsed along a line of sight perpendicular to the direction of motion, 450,000 years into the AGB evolution. This is approximately when the simulation best fits the observation. Specifically matching the position of the bow shock ahead of and across the position of the star. The density of the local ISM is a parameter set by the ram-pressure balance and is derived to be 0.03 Hydrogen atoms per cm^{-3}, lower than that derived by Martin et al. (2007) who infer 0.8 per cm^{-3}. It was not possible to reproduce the location of the bow shock with such a high ISM density and it was only after 450,000 years of AGB evolution that the tail reached the observed length, with density variations along the tail also approximately consistent with the observation.

This result implies the tail is far older than it appears from its spatial extent. The material in the tail does not instantaneously deccelerate to the ISM velocity. Instead, the gas being shed from the bow shock into the tail initially travels at 130 km s^{-1} and slowly decelerates from this velocity as it moves down the tail. Recently reported radio observations of Mira's bow shock and tail have confirmed this prediction: Matthews et al. (2008) performed observations with the Nançay Radio Telescope detecting HI line emission up to 1.5 degrees along the tail from central star, correlated with the UV emission. One of their key results is that the spectra reveal a clear slowing down of the material in the tail with increasing distance from Mira. At the furthest extent of 1.5 degrees, they find a velocity of 27.7$\pm$ km s^{-1} and extrapolate this to estimate a velocity at the extent of the UV emission of $\sim 23 \pm 3$ km s^{-1}. This is in good agreement with the velocities in the simulations described above. Matthews et al. derive an age for the tail of $120,000 \pm 15,000$ years. Taking into account the time taken for the bow shock to reach a position of ram pressure balance and for ram-pressure-stripping to begin

(∼50,000 years in the author's simulations) a total age of the structure around Mira can be estimated at approximately 200,000 years.

The emission appears to vary along the tail and naively relating emission directly to density, it would seem there are almost regular gaps of material. Martin et al. suggest these could be due to thermal pulsing events The new 120,000 year age of the tail implies interpulse periods between these 'gaps' of $\sim$ 40,000 years. The interpulse period is a strict function of the core mass of the star. Deriving the mass from the spectral type of Mira A, M7 IIIe (Castelaz & Luttermoser 1997), gives an estimate of 2.5 solar masses (Straizys & Kuriliene 1981) in reasonable agreement with the combined mass of the system of $\sim$ 4 solar masses derived by Prieur et al (2002). Vassiliadis and Wood (1993) derive an interpulse period on the thermal pulsing branch of the AGB of 80-100,000 years for a star with this mass - too long for the gaps in Mira's tail to be associated with thermal pulsing events.

Instead, the author postulated that the first gap seen 1/3 of the way downstream from Mira could be explained by the star's possible recent entry into the Local Bubble, a low-density region of about 300 light years across in which the Sun is also located. An approximate 3D map of the Local Bubble is presented by Lallement et al. (2003): on their maps Mira would be located close to the edge but inside of this shell. This would also explain the narrowness of the tail, which is not reproduced by the author's simulation: as Mira moved though interstellar space, a smaller bow shock formed much closer to the star with a narrow tail, as observed beyond the gap under discussion here. Approximately 25 light years downstream from its current location, Mira entered the lower density Local Bubble. The bow shock expanded according to the new ram pressure balance, during which time little material was ram-pressure stripped into the tail, directly leading to the gap in the tail. This also supports the low density of 0.03 Hydrogen atoms per cm^{-3} of the local medium predicted by the author's simulation.

In an effort to reproduce finer details of the structure, Raga et al. (2008) have taken the hydrodynamic modelling of Mira a step further and developed a latitude-dependent wind model. In their model, the latitude dependency, justified as a possible effect of the binary companion on the wind and supported by detection of a bipolar component in Mira's wind (Josselin et al. 2000), leads to a greater mass-loss in the plane of the binary than at the poles of this plane. The outflow velocity is adjusted inversely to conserve the outflow momentum. Otherwise, their model is essentially the same as the one of the author. Raga et al. find that they are able to reproduce the observed multiple knots with bow shocks in approximately northern and southern streams, concluding similarly to the author that there is no need for time-dependency in the stellar wind. Raga et al. find that their simulation best reproduces the knots and multiple bow shocks after 160,000 years of AGB evolution, an age consistent with the 200,000 years estimated to form the whole structure.

To investigate if the thermal pulse cycle will have any effect on the bow shock and tail, the author performed a further simulation with a time-variable mass-loss rate. In this second simulation the mass-loss rate was increased by a factor of three during the 1000-year Helium flash phase (the thermal pulse) immediately followed by a factor of three decrease during 10,000 years of quiescent helium burning with 100,000 years between flashes. The author found that this variation in the mass-loss rate did not greatly affect the characteristics of the bow shock and tail. Throughout the simulation, the bow shock is in the same position and has the same width across the central star. Structures in the tail which were a result of turbulence in the first simulation were found to be in roughly the same position, suggesting that these structures are an effect of turbulence rather than of variations in the mass-loss rate.

3. Is it a wonderful life ahead for Mira?

The presence of bow shocks ahead of AGB stars was predicted before the observation of R Hya; simulation of the planetary nebula (PN) Sh 2-188 (Wareing et al. 2006a) found that the only way to create the apparent shape of the nebula was to model both the PN phase of evolution and the preceding AGB phase of evolution. It was during the AGB phase that the shape of the PN was crucially defined by the bow shock which formed against the oncoming ISM. So, both Mira and R Hya share a similar future then, one in which they will form planetary nebulae similar to Sh 2-188 *with the shape of their planetary nebulae already defined by the bow shock we currently observe.*

An observation of Sh 2-188 is shown in figure 3 to illustrate the probable future of Mira. The central star of Sh 2-188 has been inferred to be moving at approximately 125 $\mathrm{km\,s^{-1}}$ through the local ISM. During the preceding AGB phase, a bow shock formed ahead of the star with an associated ram-pressure-stripped tail of material. In the next phase, the remaining white dwarf core of the star drove a fast stellar wind ($\sim$ 1000 $\mathrm{km\,s^{-1}}$) which swept up the circumstellar material. Initially, the swept-up shell expanded within the confines of the bow shock and would have appeared like any other symmetric ring PN, but after 20,000 years when the nebula was fading and the white dwarf cooling, the shell had expanded far enough to begin interacting with the pre-existing bow shock and rebrightened in the direction of motion, resulting in what we observe today. The faded completion of the shell behind the bow shock can be seen in the figure to the north-west of the central star, as can faint emission from the tail of far-older AGB material further to the north-west. Sh 2-188 has passed through the four general stages of the PN-ISM interaction identified by the author (Wareing et al. 2007b). In the first stage the PN expanded within the bubble of undisturbed AGB wind material behind the bow shock formed during the AGB phase. The bow shock may have been able to be observed outside the PN, as in the case of the Helix nebula. During this stage, the PN was unaffected by the ISM interaction. The second stage was entered when the PN had expanded far enough to interact with the bow shock. As the PN shell merged with the bow shock, driving another shock through it, the density and temperature of the material increased accordingly and strengthened the emission from this region, leading to re-brightening in the direction of motion, particularly clear in the case of Sh 2-188 as the stellar motion is predominantly in the plane of the sky. During this stage, the PN has begun to deviate from circularity on the sky as the nebular shell is decelerated in the direction of motion. The third stage of interaction is defined by the geometric centre of the nebula moving downstream away from the central star, also seen in the case of Sh 2-188. In the fourth and final stage of PN-ISM interaction, which is only reached by the highest velocity stars, the structure is no longer recognizable as a PN. The fast wind forms a bow shock ahead of the star and the little remaining shell material in the vicinity of the star

Figure 3. A combination of deep and shallow observations of Sh 2-188 showing the detail in the bright arc and the faint structure (with some blurring to allow combination of the images). The faint central star is indicated on the image between the markers. North is up and East to the left. This figure is a reproduction of figure 3 from Wareing et al. (2006a). Please consult that reference for full details.

is swept downstream in turbulent areas of high density and temperature. Sh 2-188 is yet to enter this stage.

Mira is moving at a high enough velocity to go through all four of these stages. Assuming the conditions of the medium Mira is travelling through don't change greatly, Mira's PN will be a scaled down version of Sh 2-188. Mira's smaller bow shock will mean that it will evolve through the four stages of interaction more quickly and most likely will appear like Sh 2-188 after only a few thousand years, rather than the estimated 22,500 year old Sh 2-188. Mira's PN will most likely be fast-evolving and short-lived.

How close Mira is to the end of the AGB phase is unknown. Given that simulations predict the effect of thermal pulsing would be difficult to observe on the structure, it is possible Mira is already undergoing these events. The mass-loss rate measured from CO observations ($\sim 3 \times 10^{-7}$ solar masses per year (Ryde et al. 2000)) suggests not, but we could be observing Mira during an interpulse period suggested by Matthews et al. (2008), especially given the considerable time required to form the long tail when compared to the estimates of the AGB phase of evolution lasting around 500,000 years.

4. Mira as a prototype for the fate of our Sun?

A comparison of Mira's future to that of our Sun is very dependent on the Sun's relative velocity through the ISM, found to be 26.24 ± 0.45 km s^{-1} (Möbius et al. 2004). At this velocity a bow shock will still form ahead of the Sun during the AGB phase. The bow shock will most likely be much further away from the Sun than in Mira's case, especially if our Sun is passing through a low-density region of interstellar space at the time. Our Sun's planetary nebula will expand and fade little affected by the local ISM. Only towards the end of its life might it have expanded far enough to interact with the bow shock, at which time it might experience a re-brightening similar to Sh 2-188. The PN would be much like that modelled by Villaver et al. (2003) and case A of Wareing et al. (2007b). The bow shock will have a tail which will carry away an appreciable fraction of the material ejected on the AGB, but given the Sun's low relative velocity the bow shock may not be observable, although Matthews et al.'s recent results suggest a tail of HI emission may be observable in the radio. This prospective future of our Sun is highly dependent on local ISM conditions. Given that our Sun is likely to travel through many high-density clouds and low-density regions (Frisch 2003) over the course of its lifetime before it even reaches the final AGB and post-AGB phases of its life, it is difficult to quantify parameters of the the AGB wind bow shock and the subsequent PN, but our solar motion through the local ISM will cause our Sun's PN to go through at least the first two stages outlined above.

5. Prospects of astrophysics from Mira

The simulations reviewed above employ relatively simple models to gain advanced understanding of the way in which Mira's cometary structure forms. There are aspects of the structure which as yet have not been reproduced and are the challenge for future simulations. The ring observed on the western side of the tail is particularly interesting. It is possible that it is a vortex ring, previously predicted by the author (Wareing et al. 2007a): instabilities at the head of the bow shock peel off downstream and form vortices in the tail, although a full ring structure has not yet been reproduced. It is also possible that this is an alternative explanation for the knots and multiple bow shocks. A fuller investigation of the vortices, which add dust and angular momentum to the ISM in structures which survive for long periods (greater than 100,000 years) in the wake, remains to be performed. With the development of adaptive mesh refinement for hydrodynamic simulations, enabling the simultaneous simulation of large and small scales, and ever-more powerful supercomputers, a full simulation of the binary system with mass loss from Mira A is becoming within the realms of possibility. This simulation may reveal the true influence of the binary companion on the wind and the effect on the bow shock, including the shedding of any vortices into the tail.

The narrowness of the tail remains difficult to reproduce in simulations. Whilst it can be explained as the effect of variation of the medium through which Mira has traveled, there may also be other factors affecting the evolution of the tail. In the author's simulations, collimation of the tail is only seen with a relative velocity above 100 $\mathrm{km\,s^{-1}}$, but not to the narrow degree observed. One possibility is that the magnetic field of the ISM is collimating the tail in a similar way to the way in which the Sun's wind collimates the tail of stellar wind particles behind the earth (Milan 2004). Gaps along the tail correspond very well with the points to disconnections in the magnetotail.

From a simple hydrodynamical ram-pressure balance argument, other environmental factors, e.g. the density of the local medium through which Mira travels, can have a strong effect on the bow shock and resulting tail. If, for example, Mira had recently been traveling through a high density medium (e.g. 100 times more dense) then the bow shock would have been closer to the star (e.g. by a factor of ten times) and the tail accordingly much narrower. This is the argument the author uses to suggest Mira entered a region of low density approximately 25 light years ago, possibly the Local Bubble. A calculation of Mira's orbital motion about the Galactic plane would reveal information about the medium Mira has passed through and the future conditions it will experience. It may also go some way to explaining the observed curvature of the tail, where the tail almost seems to bend one third the way down the tail from the star. Further investigation of the tail gas may also reveal whether it is moving purely along the tail, or whether there is a residual perpendicular motion from the effect of the orbit.

The increased age of the tail has large implications for the emission method. The emission method proposed by Martin et al. (2007) of collisional excitation is not consistent with the increased age of the tail. Clearly there must be another mechanism working here. It is possible that it is heated H2 emission, with the energy being supplied by the differential velocity between the tail and the streaming ISM. This remains to be investigated. The increased age of the tail also has large implications for the evolution of Mira. At its current mass-loss rate, over 200,000 years Mira A will have lost 0.06 solar masses of material. Matthews et al. (2008) detect 4×10^{-3} solar masses of this material. The duration of this mass-loss rate suggests that the theoretical mass-loss rates for stars on the early thermal-pulsing AGB are underestimated, a point highlighted by Matthews et al. (2008), and further investigation of Mira's cometary structure may lead to a new understanding of the whole AGB phase of evolution.

Martin et al. (2007) detected no emission at other wavelengths at their level of sensitivity, but deeper observations may reveal the cometary structure. There are already reports that the bow shock is detected in Hα (R. Corradi - private communication). Temperature and density spectroscopic diagnostics for the material in the shock region at optical and infrared wavelengths can provide context for analysis of variation of mass loss and gas to dust ratio, as well as exploration of the destruction of dust at the well defined boundary of the bow shock. The recent radio observations of Matthews et al. (2008) reveal the interesting anti-correlation of the radio emission and UV emission in close proximity to the star, which also remains to be fully explained.

It is interesting also to consider the fate of circumstellar dust as it passes through the shock. Dust will be transformed during this passage becoming interstellar dust. Slavin et al (2004) considered the shock processing of large grains and found that it is highly dependent on grain size and shock speed. Future facilities like Herschel and ALMA should be able to begin addressing this transformation of circumstellar solids into the interstellar medium, adding to the recent Spitzer spectra of R Hya.

(*a*) *One of a kind?*

Observationally, the tail of Mira is currently unique. However, all evolved AGB stars show similar or stronger winds to Mira, raising the question of whether Mira is a prototype or an exception, regarding its cometary structure. Circular shocks around AGB stars are probably known - there is a a detection of a partial HI shell around IRC +10216 (Matthews & Reid 2007) and another case for such AGB-ISM 'walls' is presented by Zijlstra & Weinberger (2002). The main observational difference between Mira and typical similar stars is in the space velocity, typical AGB stars having a velocity through space around 30 to 50 $\mathrm{km\,s^{-1}}$. At higher velocity, the tail is narrower and more collimated and the higher degree of friction between the tail and the ISM heats the surface layers of the tail, as the tail gas itself also moves at appreciable velocities with respect to the ISM. The author has suggested previously that this secondary heating has strong effects on the observability (Wareing et al. 2007c). Slower tails may not generate sufficient heating to produce observable UV emission and therefore whilst Mira-like tails may be common, albeit in most cases not as narrow, they are not evident in current emission line surveys. Mira is also relatively close and moving at an abnormally high velocity through its local surroundings, making the tail easier to detect. Radio emission may be more readily observable behind such stars. Matthews et al. (2008) draw attention to another 'plume' of HI emission stretching away from the semi-regular variable star RS Cnc (Gérard & Le Bertre 2006), which is apparently consistent with material trailing the stellar motion. They also note an analogous but shorter tail associated with another semi-regular star, X Her (Gardan et al 2006; Matthews et al., in prep.). Both stars have smaller space velocities than Mira - 100 $\mathrm{km\,s^{-1}}$ and 18 $\mathrm{km\,s^{-1}}$ respectively. Matthews et al. (2008) propose that extended gaseous tails may be common, if not a prerequisite of stars undergoing mass-loss moving through space at velocities higher than their wind velocity. These tails are predicted to be readily observable at radio wavelengths and Mira could be another prototype, this time of a class of 'Mira-tail' stars. Care must be taken though in associating HI emission, which is common throughout the Galaxy, with a nearby AGB star, although the case for Mira is clearly strong enough. Mira is, and mostly likely to remain, wonderful.

I would like to thank the many people who have collaborated with me on the subjects of this paper. Dr Tim O'Brien and Prof. Albert Zijlstra deserve a special mention. I thank STFC for previous PhD and post-doctoral funding and for supporting my current research fellowship in the Department of Applied Mathematics at the University of Leeds.

References

Bayer, J. 1603 Uranometria Omnium Asterismorum Continens Schemata Nova (Himlens uppmätning), Augsburg (1603

Castelaz, M.W., Luttermoser, D.G. 1997 Spectroscopy of Mira variables at different phases, *AJ*, **114**, 1584

Fabricius, D. 1605 Kurtzer und grndlicher Bericht, (auf der Herzogl. Bibl. Gotha, Math. 4, p.124), Hamburg

Frisch, P. 2003 Local interstellar matter: the Apex cloud, *ApJ*, **593**, 868

Gardan, E., Gérard, E., Le Bertre, T. 2006 Atomic hydrogen in asymptotic giant branch circumstellar environments. A case study: X Her, *MNRAS*, **365**, 245

Gérard, E., Le Bertre, T. 2006 Circumstellar atomic Hydrogen in evolved stars, *AJ*, **132**, 2566

Ireland, M. J., Monnier, J. D., Tuthill, P. G., Cohen, R. W., De Buizer, J. M., Packham, C., Ciardi, D., Hayward, T., Lloyd, J. P. 2007 Born-again protoplanetary disk around Mira B, *ApJ*, **662**, 651

Josselin, E., Mauron, N., Planesas, P., Bachiller, R. 2000 Strong asymmetries in the neutral envelope of Mira, *A& A*, **362**, 255

Karovska, M., Schlegel, E., Hack, W., Raymond, J. C., Wood, B. E. 2005 A large X-ray outburst in Mira A, *ApJ*, **623**, L137

Knapp, G. R., Pourbaix, D., Platais, I., Jorissen, A. 2003 Reprocessing the Hipparcos data of evolved stars. III. Revised Hipparcos period-luminosity relationship for galactic long-period variable stars, *A& A*, **403**, 993

Lallement, R., Welsh, B.Y., Vergely, J.L., Crifo, F., Sfeir, D. 2003 3D mapping of the dense interstellar gas around the Local Bubble, *A& A*, **411**, 447

Martin, D.C. et al. 2007 A turbulent stellar wind wake trailing 30,000 years behind Mira, *Nature*, **448**, 780

Matthews, L. D., Karovska, M. 2006 First resolved images of the Mira AB symbiotic binary at centimetre wavelengths, *ApJ*, **637**, L49

Matthews, L. D., Libert, Y., Gérard, E., Le Bertre, T., Reid, M. J. 2008 Discovery of an HI Counterpart to the extended tail of Mira, *ApJ*, *accepted*, arXiv:0805.1730

Matthews, L.D., Reid, M.J. 2007 Very Large Array observations of HI in the circumstellar envelopes and asymptotic giant branch stars, *AJ*, **133**, 2291

Milan, S. 2004 A simple model of the flux content of the distant magnetotail, *J. Geophys. Res.*, **109**, A07210

Möbius, E. et al. 2004 Coordinated observation of local interstellar helium in the Heliosphere: Synopsis of the interstellar He parameters from combined neutral gas, pickup ion and UV scattering observations and related consequences, *A& A*, **426**, 897

Prieur, J.L., Aristidi, E., Lopez, B., Scardia, M., Mignard, F., Carbillet, M. 2002 High angular resolution observations of late-type stars, **ApJSS**, **139**, 249

Raga, A., Cantó, J., De Colle, F., Esquivel, A., Kajdic, P., Rodríguez-González, A., Velázquez, P. F. 2008 A latitude-dependent wind model for Mira's cometary head, *ApJ*, **680**, L45

Ryde, N., Gustafsson, B., Eriksson, K., Hinkle, K.H. 2000 Mira's wind explored in scattering Infrared CO lines, *ApJ*, **545**, 945

Sigismondi, C. 2002 Mira Ceti and the Star of Bethlehem, *Quodlibet*, **4**, 1

Slavin, J.D., Jones, A.P., Tielens, A.G.G.M. 2004 Shock processing of large grains in the interstellar medium, *ApJ*, **614**, 796

Straizys, V., Kuriliene, G. 1981 Fundamental stellar parameters derived from evolutionary tracks, *Ap& SS*, **80**, 353

Ueta, T. et al. 2006 Detection of a Far-Infrared bow shock nebula around R Hya: the first MIRIAD results, *ApJ*, **648**, L39

Vassiliadis, E., Wood, P.R. 1993 Evolution of low- and intermediate-mass stars to the end of the asymptotic giant branch with mass loss, *ApJ*, **413**, 641

Wareing, C. J., O'Brien, T. J., Zijlstra, A. A., Kwitter, K. B., Irwin, J., Wright, N., Greimel, R., Drew, J. E. 2006a The shaping of planetary nebula Sh 2-188 through interaction with the interstellar medium, *MNRAS*, **366**, 387

Wareing, C. J., et al., 2006b Detached shells as tracers of asymptotic giant branch-interstellar medium bow shocks, *MNRAS*, **372**, L63

Wareing, C. J., Zijlstra, A. A., O'Brien, T. J. 2007a Vortices in the wakes of AGB stars, *ApJ*, **660**, L129

Wareing, C. J., Zijlstra, A. A., O'Brien, T. J. 2007b The interaction of planetary nebulae and their AGB progenitors with the interstellar medium, *MNRAS*, **382**, 1233

Wareing, C. J., Zijlstra, A. A., O'Brien, T. J., Seibert, M. 2007c It's a wonderful tail: the mass-loss history of Mira, *ApJ*, **670**, L125

Zijlstra, A. A., Weinberger, R. 2002 A Wall of Dust around a Proto-Mira?, *ApJ*, **572**, 1006

AUTHOR PROFILE
Christopher J. Wareing

Christopher Wareing was born in 1978 in Manchester. He completed a first degree at the University of Manchester and than a Ph.D. at Jodrell Bank Radio Observatory, part of the University of Manchester. His Ph.D. research resulted in a thesis entitled 'Hydrodynamical modelling of planetary nebulae and their interaction with the interstellar medium', submitted in 2005. He then spent two years working part-time as a post-doctoral research assistant with Prof. Albert Zijlstra at the University of Manchester, where the majority of his work on Mira was carried out. At the same time, he also managed the Royal Institution of Great Britain's 'Science for Schools' project in the North West of England, taking scientists into schools to excite and enthuse students from 8 to 18 years of age about science, technology, engineering and mathematics. In August 2007, he moved to the University of Leeds and took up a post-doctoral research fellowship under Dr Rainer Hollerbach working on the evolution of magnetic fields in neutron stars. His main research interests are in the application of numerical hydrodynamics to modelling of the late stages of stellar evolution. He is a keen mountaineer.