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Mira Variables

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Abstract

The current status of research on Mira variables is informally reviewed. Observable properties of Miras -- light curves, spectra, luminosities -- are related to our current understanding of their internal structure and evolutionary status. The importance of the mass loss caused by the Mira pulsation in producing white dwarfs is stressed. Although our understanding of the causes and consequences of Mira variability have advanced enormously during the last 25 years, there are still some very puzzling phenomena among the Miras and related variables. Continued observations are needed to solve these puzzles and to verify the effects of the mass loss on the stellar structure.

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Mira variables are red giant stars of spectral types M, S, or C with emission lines; they have light curves with relatively regular variation and visual amplitudes greater than 2.5 magnitudes. Most Miras have periods from 200 days to 500 days. Because Miras are intrinsically bright, and because their amplitudes are large and their periods are long, Mira variable light curves are nearly always determined from visual estimates compiled by the AAVSO and related organizations.

The significance of the classification criteria

The four main criteria for classifying a star as a Mira -- regularity, visual amplitude, spectral type and luminosity class -- refer to very different properties of these stars.

<u>The spectral types of the Miras are those of very cool stars</u> -- stars with effective temperatures around 3000K, or about half the surface temperature of the sun. The Miras are all found among the coolest known stars; in fact among giant stars the coolest stars are all Miras or OH-IR stars. The standard spectral classification sequence is a temperature sequence, with a separation into composition classes at the cool end:

O	B	A	F	G	K	M
					R	N
						S

Hot .... Cool

For the warmer spectral types there is no separate classification for stars of different composition; why does the sequence split into three for the coolest stars? There are two reasons for this split: (1) In the atmospheres of cool stars molecules are able to form. Small differences in composition make a large difference in the molecular abundances. Thus for example if there is more oxygen than carbon present, all the carbon will be tied up in CO; if there is more carbon, some of it will form C_2 and/or CN, both of which will be obvious in the spectrum. (2) The coolest giants, including the Miras, are very evolved stars; material that was deep inside the star and therefore had its composition modified by nuclear reactions has been mixed to the surface, altering the surface composition and thus the spectrum for these stars.

Miras are giant stars: they have much higher luminosities and lower surface gravities than, for example, the sun. While Miras probably typically have masses around one solar mass, their diameters are 2-300 times the diameter of the sun. This makes their surface gravities only about 1/40000 to 1/90000 times that of the sun. One consequence of this low surface gravity is that the atmosphere is relatively loosely bound to the star, and forms a kind of fuzzy envelope around it. In an often-quoted remark, Bob Wing once characterized the Mira variables as "jelly-fish stars" (Wing 1980).

The luminosity of a star depends on the surface area (L proportional to diameter squared) and surface "effective temperature" (L proportional to temperature to the fourth power). Although the Mira effective temperatures are only about 1/2 that of the sun, their very large radii make them very luminous -- typically 5000-10000 times the luminosity of the sun. They are using up their nuclear fuel very rapidly, and cannot possibly last at this rate more than a few million years.

The light curve of a typical Mira variable is sketched in Figure 1. If the light curve is translated from magnitudes into intensity or flux units, as in the bottom part of Figure 1, then we see that the large amplitude and rapid rise are consistent with an abrupt and almost explosive event on the star at the phase of maximum light. We identify this "event" with the emergence of a shock wave into the atmosphere of the Mira; the shock wave is in turn a consequence of regular pulsation taking place beneath the visible surface. The presence of emission lines in the spectra of Miras at some phases are an indication that there is material at high temperature (5,000-10,000K) in the atmospheres of these stars; this is further evidence that there are shock waves in the atmospheres of the Miras. Theoretical models for the atmospheres of pulsating Mira variables by George Bowen (1986) and others support this interpretation.

It is interesting to look through the compilation of mean Mira light curves assembled and published by Leon Campbell of the AAVSO 30 years ago (Campbell 1955). The light curves are displayed in order of increasing period, and this makes trends with period quite apparent. The "Miras" with periods less than about 200 days have light curves with relatively small visual amplitudes that are symmetric about maximum light. As the period increases, the light curves increase in amplitude and the rising branch becomes shorter than the declining branch. Finally for periods greater than about 400 days strange bumps on the rising or the declining light curve or even double maxima are seen, and the amplitudes in some cases become as large as 7-8 magnitudes.

In Report 38 of the AAVSO the light variation of a large number of Mira variables are displayed for a 1000-day interval. The format chosen shows nicely the effect of the accumulated efforts of many observers in defining the light curves. The roughly 3 year interval includes 2-4 maxima for each star, so that the typical cycle-cycle variations may be seen. Light curves for three of my favorite Miras from Report 38 are reproduced in Figure 2; anyone seriously interested in Miras should get a copy of this report and study it carefully.

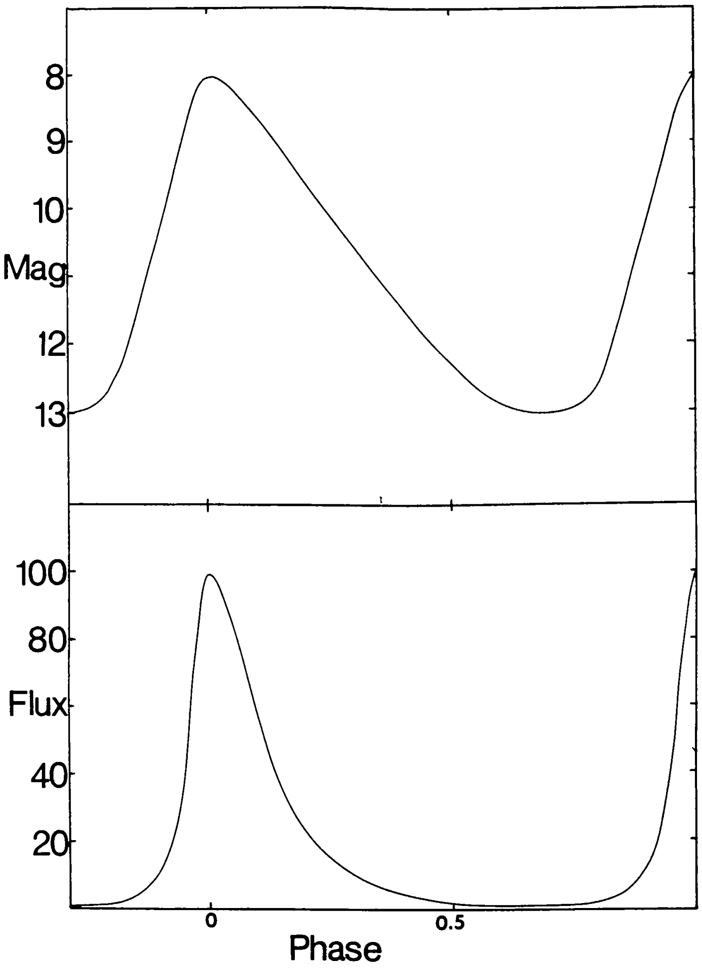

Figure 1. Representative or "generic" light curve for a Mira variable. The magnitude variation is shown at the top, the corresponding brightness (flux) variation at the bottom. Note the relatively rapid rise and slow decline. About 75% of the total energy is emitted during 25% of the cycle near maximum light; this corresponds to the phase when the apparent stellar surface coincides with a rising shock wave in the atmosphere.

Closely related (?) classes of variable stars

There are other "long-period variables" that are also giant stars but that are not Mira variables. If the amplitude is not 2.5 magnitudes in the visual, but the light curve is still relatively regular, the star is classified as an SRa variable. If the light curve is less regular, but still suggests some characteristic period, then the star is an SRb variable. If the spectral type indicates a warmer star than class M, C, or S then it is an SRd variable; SRc variables are "supergiants" rather than giants. (Technically supergiants are more massive stars than giants, and they have a very different internal structure.)

The very luminous "OH-IR" stars, with so much material around them that we cannot see the star directly, have periods from about 500 days to perhaps 2000 days in some cases. (Since these have only been observed for about the last decade, the longest periods are not yet well determined.) The relation between the period and the luminosity of these objects (about the only observable quantities) seems to make a

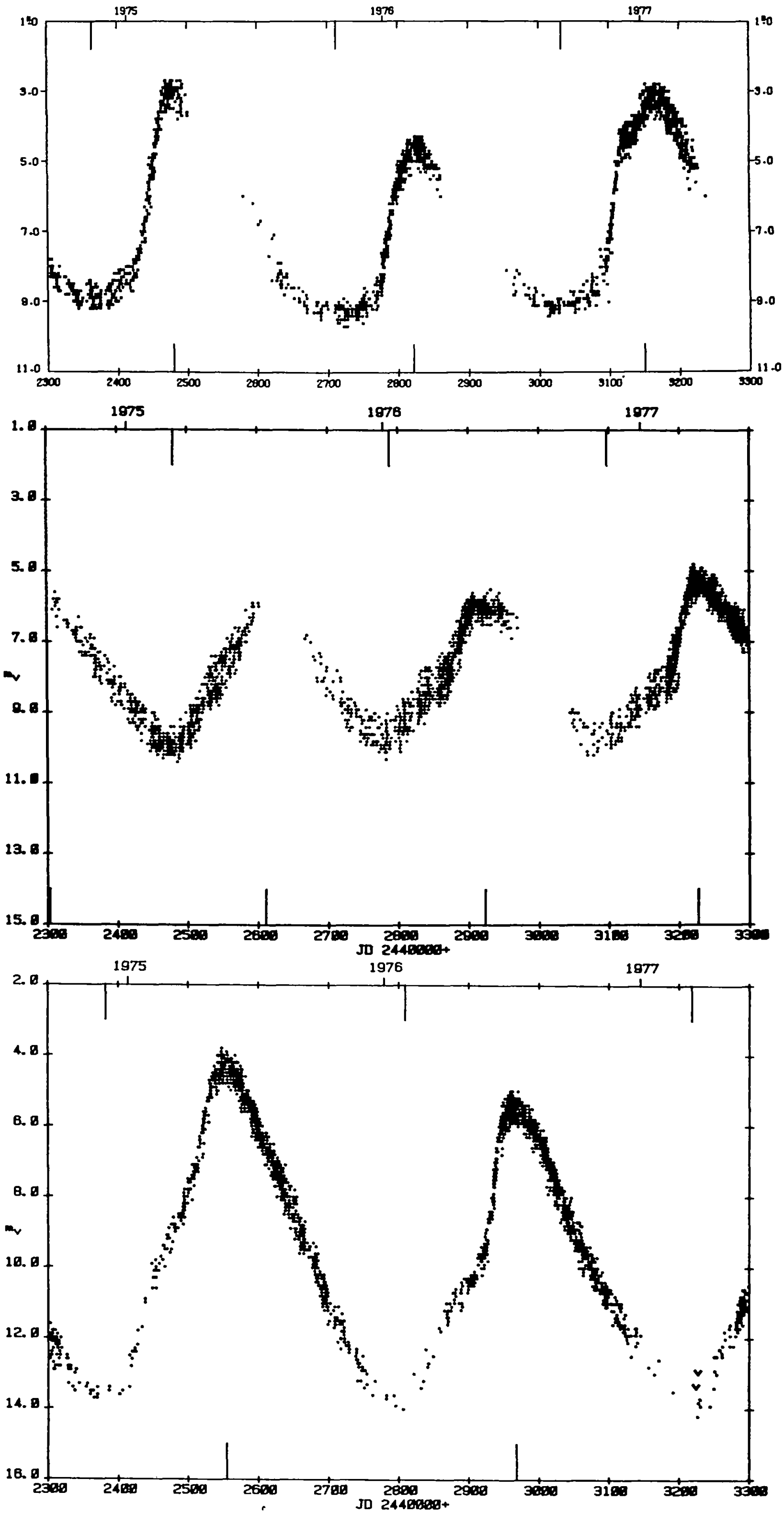

Figure 2. Light curves for o Ceti (Mira), R Leonis, and Chi Cygni from Report 38 of the AAVSO. Mira and R Leonis have similar periods and are probably at about the same distance from us; R Leo appears fainter due to more atmospheric absorption. Chi Cygni has a somewhat pecular (S-type) spectrum and a very large amplitude.

smooth extension of the relationship for Miras. Thus we suspect that these are really long period Miras whose mass loss rates are so high that we cannot see the star through the material it has ejected.

The evolutionary status and internal structure of Miras

Miras are highly evolved objects -- they are very close to the end of their nuclear fuel supplies, and will soon be on their way to become white dwarf stars. The location of the Mira variables in the Hertzsprung-Russell diagram is shown in Figure 2, together with evolutionary tracks from theoretical calculations for stars that are likely to develop into Miras.

Before a star becomes a Mira it must go through a sequence of stages. First, the star forms by the gravitational contraction of a cloud of interstellar material (for a one solar mass star this takes about 10^7 years). Then there is a very long stage during which its luminosity is produced by the conversion of hydrogen into helium (4H --> He + energy in a process involving several intermediate steps) in the core of the star. This stage is called the main sequence stage, and lasts about 10^{10} years for a star of one solar mass. When about 10% of the material in the star -- the central 10% -- has been converted to helium, this core contracts and the conversion of H to He continues in a shell around the core. At this time the star expands to 50-100 times its main sequence size, and becomes a red giant for the first time; this stage lasts about 500 million years.

When the helium core has grown to about half a solar mass, the reactions 3He --> C and He + C --> O are ignited in the core, and the star may shrink. If the star has a mass around 0.6 solar masses then the star will probably become an RR Lyrae star at this stage; if it has a mass at least 5 solar masses then it will become a Cepheid; if it has a mass intermediate between these two it will remain a red giant -- a "clump giant".

When the material near the center of the star has become almost entirely C and O the core shrinks, and the star for the second time "burns" hydrogen into helium in a shell around the core. As for the first giant stage, the star expands and moves into the region of the red giants; we say that it becomes an asymptotic giant branch (AGB) star. During this stage, the hydrogen burning shell keeps adding to the helium layer around the C/O core; whenever this becomes thick enough, the He will "ignite" again and add more C and O to the core. While the He is burning the He shell expands, shutting off the H burning shell. The AGB stars thus spend about 80% of their time converting H to He and 20% converting He to C and O.

As the star switches back and forth between the two sources of fuel (H and He) material is mixed from the region near the core into the convective envelope, and thence upward to the surface. This mixing takes place in an astronomical blink of an eye; the material reaches the surface in under 10,000 years. We know this because the unstable element Technetium is observed in the spectra of Miras; this element decays radioactively in about 10,000 years. Steve and Irene Little, frequently seen at AAVSO meetings, have made most of the observations of Technetium in Miras (see Little-Marenin & Little 1979, for example).

There is another observational clue that supports the theoretical picture I have just drawn. During the transition from H to He burning the stellar radius is expected to change; this in turn alters the period of the star. At least two Miras -- R Aql, R Hya -- have parabolic O-C diagrams indicating that their periods are changing rapidly, and Peter Wood of Australia has shown that these O-C diagrams can be well matched by the theoretical calculations for an AGB star recovering from the sudden ignition of He, a "helium shell flash" (Wood & Zarro 1981). If this interpretation of the O-C diagrams of R Aql and R Hya is correct, then ultimately we should see all Miras go through this "shell flash" stage. Theoretical calculations indicate that the stage of rapidly changing period should last about 100 years, and recur every 1000 to 10,000 years. If we observe 100 Miras for 100 years we should be able to catch at least one as it starts its shell flash.

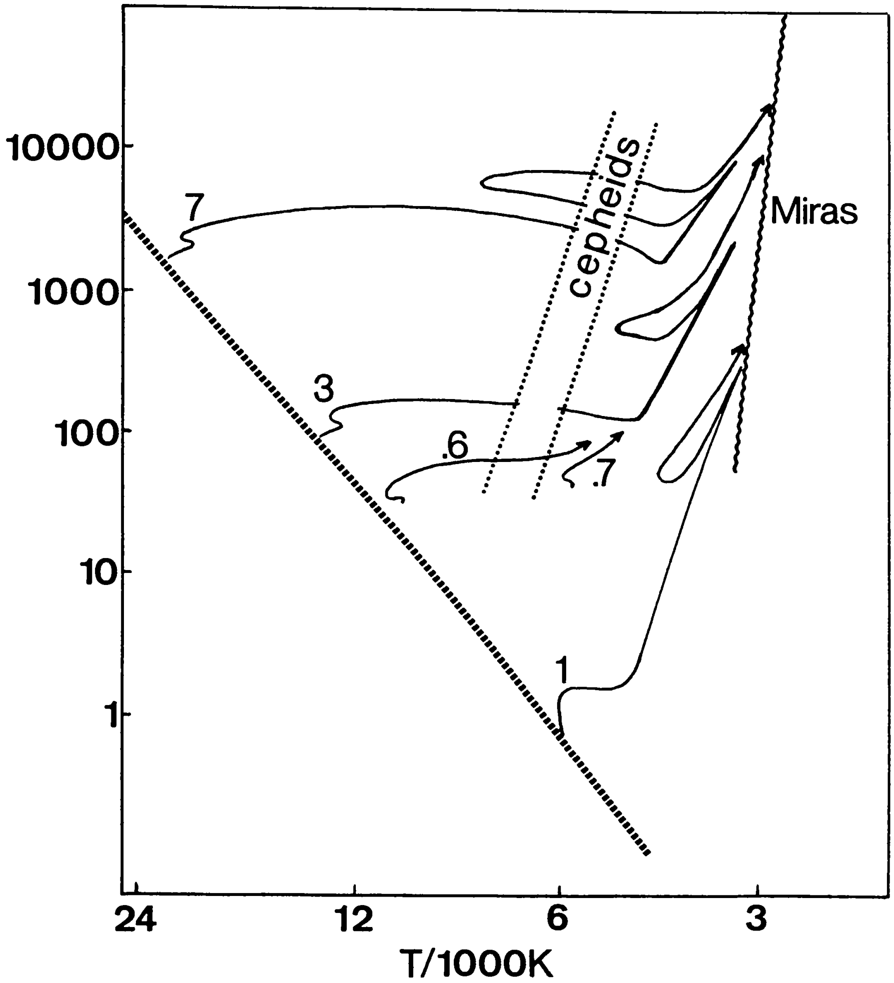

Figure 3. Evolutionary tracks for stars that may become Mira variables. The 1 solar mass star stays cool (remains a red giant, a "clump giant") while it burns its central helium, then goes on to become a Mira. The 7 solar mass star "loops" to the blue for its helium burning stage, becoming a Cepheid before it becomes a Mira (or possibly an OH-IR star) on the Asymptotic Giant Branch. A star with a mass around 0.6 solar masses becomes an RR Lyrae variable during its central helium burning stage; it is not yet clear whether any of these stars can go on to become Miras.

Some long period variable stars have regular, large-amplitude variability and appear to be normal Miras for a dozen or more cycles, and then suddenly "switch" to a low-amplitude or non-varying state. Some of these objects have been observed to switch back and forth several times; most have only been observed to switch once. This sort of switching is not understood theoretically; it may occur in some cases as a result of the shell flash, or it may represent some instability in these stars. Some of us are now beginning to suspect that if we wait long enough all Miras will switch "off", and some small amplitude semi-regulars will switch "on" as Miras. However it will require much patience and many more years of observing Miras before we can determine if this odd behavior really is universal.

Importance of the Mira stage of evolution

Mira variables are found at the tip of the asymptotic giant branch; they are stars that are very nearly out of the fuel that they are capable of using. During or immediately following the Mira stage the material in the convective "envelope" (= everything but the core) is lost to the star -- probably as a direct consequence of the Mira pulsation itself. This rapid mass loss limits the Mira stage to about 1 million years. When the envelope is nearly gone, a stage of particularly rapid mass loss with steadily increasing velocity produces a planetary nebula; the now-revealed core is seen as a hot central star. When virtually all of the hydrogen is gone from the central star it begins to shrink and cool, slowly becoming a white dwarf. Most Miras make white dwarfs with masses around 0.6 - 0.7 times the mass of the sun; the Mira wind has stripped away the rest of the star.

If the AGB stars did not become Mira variables, this mass loss would not occur and the carbon-oxygen cores of these stars would continue to grow. Stars with masses greater than about 1.5 solar masses would explode as supernovae when the core mass reached 1.4 solar masses; we would then have about ten times as many supernovae as we have now.

Past, Present and Future AAVSO observations of Miras

Over the past 75 years the AAVSO has collected observations for about 100 Miras. O-C diagrams constructed from these Mira light curves indicate that the periods of these stars are not perfectly stable; there are "kinks" in the O-C diagrams indicating abrupt or continuous changes in the periods of a few percent every few decades. These long term O-C diagrams should allow us to detect slow changes in the masses and radii of these stars as they evolve, as well as the more abrupt and dramatic cases where a shell flash occurs. However due to the kinky behavior of the Miras, it will be necessary to continue the Mira observations for at least another 75 years before unambiguous conclusions can be drawn.

During the past 25 years there have been enormous advances in the observational techniques used to study Miras and related stars. Professional astronomers have observed Miras in the ultraviolet (from space), the infrared (from the ground and from space), and the radio regions of the spectrum. Each new observing "window" has led to new insights into their behavior. Also important is the increased use of photometric equipment by amateurs; this will allow us to study the lower-amplitude semi-regular variables as well as to look for more subtle features in the light curves of the Miras. During the past two decades the luminous "OH-IR stars" have also been discovered, and have provided additional clues about the processes that take red giants into planetary nebulae and white dwarfs.

On the theoretical front, the first big steps towards understanding the Miras have been made. When as a graduate student I first encountered these stars I asked my professors: What masses do these Miras have? What evolutionary stage are they in? Is their variability due to pulsation or something else? No one knew. Now, I am able to sketch for you a fairly clear general picture, well supported by observations, although many aspects remain puzzling. We do not yet understand how these stars change their periods and/or their amplitudes abruptly, nor do we understand the origin of the cycle-to-cycle changes in their light curves. We also do not know how universal the "switching" behavior is, nor its cause.

During the next 25 years, we need to extend the light curves of the Mira variables, improve our analyses of these light curves and of the O-C diagrams, determine the light curves of the semi-regular classes of variables and find out how they are related to the Miras, and monitor the colors and spectra of more red variables. At the same time the theoretical calculations need to be improved until they are capable of predicting in some detail the behavior of the Mira variables -- light curves, spectra, etc.

I will end with a plea to the observers: While observations of other classes of variable stars are important and can seem more exciting than the monitoring of slowly varying Miras, continuing to monitor the long period variables is vital for the development of our understanding of stellar evolution. These stars are also capable of surprising behavior, even after 75 or 100 or 200 years of regularity. Please continue to observe the Miras!

Acknowledgments

No paper on Mira variables is complete without an acknowledgment for the dedicated observers of the AAVSO. The value of the accumulated millions of observations of the Mira variables is inestimable. It has been a particularly great pleasure for me to participate in this celebration of the 75th anniversary of the association and the dedication of the Clinton B. Ford Astronomical Data Center.

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