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RECENT WORK ON MIRA VARIABLES

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(The following discussion is based on a transcription of a talk by Lee Anne Willson and Thomas G. Barnes during a joint meeting of the AAVSO and the Houston Astronomical Society in the spring of 1980.)

TGB: We would like to introduce you -- those of you who have not already met them -- to long-period variables, and to share with you some of the views of the professionals. I will start off by giving an introduction to the "average" properties of long-period variables and explain why we are interested in them. Then Lee Anne will tell you about them in more detail.

According to the definition given in the General Catalogue of Variable Stars (GCVS), which is produced by the Russians for the International Astronomical Union and is the "bible" of variable stars, there are three types of stars that fall into the general class of "long-period variable". First of all, there are the Mira stars, which have very large visual amplitudes--by definition, larger than 2.5 magnitudes--and this makes Miras exciting to observe. They also have long periods, ranging from 80 days to nearly 1000 days, although the bulk of them are concentrated between 130 days and 450 days. So their typical period is about a year, and that makes them hard to observe. It takes years to complete your observations on such stars, and that makes it challenging.

They are giant stars, many times larger than the sun, and I'll return to that.

Their spectra are of class M, showing dark molecular bands and indicating that the surfaces of these stars are quite cool, with temperatures about one half that of the sun's surface.

Next are the semi-regular variables, and there are four types of them differing somewhat from the Miras, but I'll mention only two. The SRa types have smaller visual amplitudes, although their periods are roughly the same as the Miras'. They are giant stars with spectral types like the Miras'. So the Miras and the SRa stars may really be the same thing, except for their amplitudes.

The SRb stars are also similar, except that their variations are somewhat more erratic. For example, they might have a period of 30 days this year and 35 days next year.

These are the three types we usually mean when we talk about long-period variables, but I will restrict myself to the Miras, as these are the ones that have been studied more thoroughly.

What makes these stars interesting?

First, of course, is the pulsation. It makes the stars stand out, and we want to know what causes the star to swell up and then shrink. Among the pulsating stars, Miras are the least understood, because their atmospheres are very complicated. Furthermore, we would like to utilize that variation to learn something about the internal structure of the star that cannot be determined for non-variable stars. Finally, we would like to use the pulsation to calibrate several properties of the stars. For example, for Cepheid variables the period correlates very closely with the total luminosity of the star, and by comparing this luminosity with the apparent brightness, we can determine the star's distance. The Miras also show a relationship between period and luminosity, but it is not as neat and clean as it is for the Cepheids.

Miras are also interesting from the standpoint of stellar evolution. It looks now as though most stars that are similar in mass to the Sun -- from a little bit less massive up to about three times the Sun's mass -- turn into Mira variables as they come near the end of their life. It is also possible, although this is less sure, that planetary nebulae (such as the Ring Nebula in Lyra) are formed when Mira stars blow off their outer layers.

By studying the Miras we also learn something about the nuclear reactions that take place in the invisible heart of the star. It seems quite likely that the differences in chemical composition seen among the cool stars originate deep in the interior. The matter is then circulated to the surface, where it can be studied.

Miras are also interesting because they lose matter from their surface into space. When examined with radio or infra-red receivers, they show radiation coming from very cool matter that surrounds the star -- rather like a cocoon around the star. There is evidence in the spectrum that matter is leaving the surface of the star, somewhat the way matter leaves the Sun in the "solar wind." The matter lost in this way will mix with the interstellar medium and become the raw material for the next generation of stars. We would like to know its composition so we can predict what kinds of stars will come next in the history of the Galaxy. In this way, Miras tell us something about the re-cycling of material in the Galaxy.

Finally, they are interesting from the viewpoint of galactic structure because they are bright and their large amplitude makes them easy to find. There are more Miras known than any other kind of variable, and they are seen throughout the Galaxy. They can be used as probes of the distribution of stars and the motions of material in the Galaxy. Also, they have a wide range of ages, from the Sun's to about twice as great, so we can determine where stars of different ages occur in the Galaxy.

That is why we are interested in Miras, but how do we get the data for these studies?

From the apparent brightness and the distance, we can compute the luminosity. Getting the apparent visual brightness is easy -- we just use something like a light meter -- but to get the distance is very difficult. The most desirable way would be to measure the "trigonometric parallax". We look at the star first from one side of the Earth's orbit and then look at it again six months later. If the star is close enough it will appear to have shifted slightly on the sky, by an amount depending on its distance. Unfortunately, none of the Miras is close enough for this measurement to be reliable. Alternatively, we would like to find Miras in clusters of stars, because then we can use the known brightnesses of other stars in the cluster to determine the distance, but there are very few Miras in clusters. So we end up using very complicated statistical methods based on the motions of Miras across the sky. This gives an average kind of number, but it isn't worth very much. But when you get to the bottom of the barrel, you use what is left.

Once we have the distance, we can determine the luminosity, the total energy emitted per second. This is not just the energy in the visible part of the spectrum, but that emitted at other wavelengths as well. In fact, the infra-red is where most of the energy is emitted by such cool stars. Because of the uncertainties in the distances and in the corrections for infra-red emission, the computed luminosities are not well determined. The dimmest ones are roughly 2500 times as bright as the Sun. Those are the Miras with periods around 150 days. The Miras with periods around 450 days are much brighter: about 10,000 times the brightness of the Sun. So these are very bright stars.

How hot are they? We can tell they are cool by looking at the red color and the absorptions in the spectrum due to molecules such as titanium oxide, zirconium oxide, and other esoteric substances. Measurements for the visual part of the spectrum give about 2000° - 3000°K. (The Sun is about 5800°K at the surface.) But temperature measurements in the infra-red, where most of the energy is radiated, give 3000° - 4000°K. Now, that is very puzzling, as most stars appear to have the same temperature when measured at all wavelengths. What appears to cause this is the very thick atmosphere of a Mira star. The top of the atmosphere is cool and the bottom is hot. In the infra-red we see the deeper, warmer layers, but in the visual, we see only the higher, cooler levels. Probably the temperature of what you would call the "surface" of Mira is about 3200°K.

In addition to the luminosity and the temperature, the size of the star is important. The most direct way of getting that is to measure the angular diameter and the distance of the star; then some simple trigonometry will give the diameter. But when we observe the angular diameter of a star with such a thick atmosphere, we are not sure just what is being measured. Is it the outer part of the star or is it a layer that is deeper in? These measurements give sizes that are 600 to 1200 times the radius of the Sun. Those figures make most astronomers uncomfortable, because that is a very large star. By combining the luminosity and temperature, and using the laws of radiation, we can also compute the diameter indirectly. Doing that we get 300 to 600 times the radius of the Sun. The nearest we can come to a concensus seems to be that a Mira with a period of 150 days will have a radius of about 150 times the Sun's, and one with a period of 450 days has a radius 450 times the Sun's. But not all astronomers agree with this conclusion. (Just for comparison, the orbit of Mars has a radius 350 times the radius of the Sun.)

Another thing we would like to know is the mass. How much matter is in the star? The only way we can get the mass with any reliability is to use Newton's law of gravity for a binary star. From the period and the size of the orbit in a binary, we can calculate the mass. In fact, that is the only way the mass of any star can be determined reliably. There are two Miras for which this can be done: X Ophiuchi and Mira, itself. The estimated period of Mira's orbit is about 260 years. For X Ophiuchi it is about 550 years. Obviously we don't have the whole orbit for either binary, so the calculation is risky. Nonetheless if we press on and do it anyway we get something like 0.8 to about 3.0 times the mass of the sun. These numbers agree fairly well with the masses predicted by stellar evolution calculations.

Next, I would like to say something about the surface composition of these stars. For most stars, the composition is about two-thirds hydrogen, one-third helium, with a few percent made up of all the other elements. For cool stars it is very difficult to derive the elemental composition from the spectrum. There are just so many lines that you can't untangle them all. Also we have to account for the elements bound up in various compounds, such as titanium oxide, and we don't know enough about the chemistry in Mira atmospheres to be able to calculate these abundances at all well.

It appears, however, that the short-period Miras have very little besides hydrogen and helium, while the longer-period Miras are quite a bit like the Sun in their compositions.

Finally, I would like to say a few words about the ages of Mira variables. From the fact that Miras are giant stars, we know they must be late in their lifetimes. Their nuclear fuel supply is running out. Stellar evolution calculations based on the apparent masses of Miras (0.8 to 3 times the Sun's mass) lead to ages of about 10 billion years for the short-period, low mass Miras, and about 3 billion years for the long-period, higher mass Miras. These compare with 4.6 billion years for the Sun.

As you can tell from this talk, our knowledge of Miras is limited. This situation will be improved as more observations are obtained and more theory developed to interpret the observations.

You can help in this endeavor.

Because Miras are variable stars, it is important to know the point in the cycle at which one's observations are acquired so the data can properly be related to other observations of the star. Indeed, many important observations need to be acquired at particular times in the cycle. By keeping track of the Mira light curves through their observations, amateur astronomers enable the professionals to pin-point the times when major telescopes and their instruments can most profitably be brought to bear.

We not only appreciate the help; we depend on it.

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<u>Question</u>: If a Mira star has a composition and a mass like the Sun's, how can it be so much cooler?

<u>TGB</u>: It can get that way by being much older than the Sun. It is much larger than the Sun so that the atmosphere we see is farther from the nuclear fusion in the core, and thus cooler.

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<u>LAW</u>: Now that Tom has tried to convince you that we can't learn much about these stars by observing them, I'll try to convince you that we can learn something by doing a lot of theory and a little bit of observation.

For convenience in describing a Mira star, let us define four distinct regions in the star where interesting phenomena occur. Figure 1 shows these four regions. At the center of the star is a "core", defined to be that part of the star where nuclear reactions are taking place. The core of a Mira is basically a white dwarf surrounded by an active shell of material -- active because that is where the nuclear reactions are happening. A white dwarf, by the way, is about the size of the earth, or just a few thousand kilometers wide. Around the core is an "envelope" -- that part of the star which lies between the core and the atmosphere. The "atmosphere" is defined simply as that part of the star which we can observe; it is the only part that gives us direct information. Since stars are gaseous throughout, they have no solid or liquid surfaces; astronomers use the term "surface" loosely to denote the bottom of the atmosphere, that is, the deepest layer which can be observed directly. As Tom pointed out, the atmosphere is very thick, and the apparent size of the star can vary by a factor of two depending on the wavelength you use. For normal stars, in contrast, the atmosphere is only a small fraction of a percent of the radius.

To visualize the proportions, imagine a grain of sand (representing the core) in the middle of a large room (representing the envelope). The core is very tiny compared with the dimensions of the Mira -- but the core produces all the luminosity of the star.

Mira variables also have "circumstellar envelopes" outside their atmospheres. This envelope is usually too tenuous to be detected without a radio telescope, infrared detectors, or other special techniques.

Each of these stellar zones has a special importance for the star. Without a core generating energy we wouldn't see the star. The envelope is where the pulsations occur. (The core generally doesn't even notice that there are pulsations going on.) The atmosphere is the source of the visible spectrum, and is a region where shock waves convert hydrodynamical energy into both visible radiation and a stellar wind. The circumstellar envelope is created by mass-loss from the star; this mass-loss is one of the most important features of Mira stars.

The diagrams in Figure 2 are an attempt to make pulsation theory look simple. Usually, a "pulsation theory" is a very large computer program, and you treat its pronouncements as though they came down from the Mountain. If it says "this is the way things are," then this is the way things are!

The simplest pulsation of a Mira star takes the whole star inward and outward in synchronism. This is for the "fundamental" mode. The outer parts of the envelope move a great deal; the center is, of course, motionless.

In the "first overtone" pulsation, part of the star is moving inward while another part is moving outward. At the "node" there is no motion. So you can't tell from looking at the outside what the inside is doing. The pulsation could be in a high overtone, complicated on the inside, but looking the same on the outside. The motions are very similar to what happens when you excite a pipe-organ tube, and just as in that case, the higher overtones are more difficult to keep going.

We can determine which mode is involved most easily by using a theoretical relationship between period, mass, and radius:

$$P\ (M/R^3)^{\frac{1}{2}} = Q$$

The period (P) is determined by people like you of the AAVSO, so we can look it up in the catalogue. As for the mass (M), the Miras must have come from stars that are between 1.0 and 3.0 times as massive as the Sun. They may have lost some mass, but they can't have lost too much or they wouldn't be so bright. The radius (R) is the bad guy. It enters the relationship as the square-root of the cube, and we have an uncertainty by a factor of two in the radius. The term Q on the right-hand side is called the "pulsation constant," because the harmonics for stars of a particular type each have their own value of

Q, and Q usually changes slightly or not at all if M or R changes. The pronouncements of pulsation theory say that a Mira star pulsating in the fundamental mode will have $Q_f = 0.1$ days; for a Mira star pulsating in the first overtone $Q_1 = 0.035$ days. This is a factor three smaller, but the difference is not larger than the uncertainties in the radius. So one of the big arguments today is, which mode are the Miras pulsating in, the fundamental or the first overtone? That is, we need to know how big the stars are in order to know what their insides are doing.

Now here comes the sneaky part. Can we find some combination of mass and radius that might be easier to measure? One combination would be surface gravity, which is proportional to the mass divided by the square of the radius. One way to measure gravity is to bounce something. Remember, the astronauts could jump higher on the moon because its gravity is smaller. In the Miras, the pulsation makes the atmosphere bounce by way of "shock waves."

In a shock wave, the density, the velocity, the pressure and anything else you care to measure, change abruptly -- essentially, instantly. An example that we are familiar with is the flow of traffic through a construction zone (Figure 3). The traffic comes in at, say, 55 miles per hour with a nice separation between the cars. Then it hits a 5-mile per hour construction zone, and it is bumper-to-bumper from there out. The change in speed brought about a change in the density, and both are abrupt. If the cars were originally separated by more than ten car lengths, the congestion won't be too severe, but if they are close together before they arrive at the construction zone, we will have a propagating shock as the cars pile up and the congestion moves up into the stream of cars.

A similar thing happens in the Mira stars, although the picture is a little more complicated. We visualize a shock propagating out through the atmosphere, with the material behind it moving upward and the material above it falling back down, having been pushed up by a previous shock.

There are two ways we can detect these shocks. The first is by observing the strong emission lines that are produced by the heated gas behind the shock. (The presence of emission lines, bright lines in the spectrum, is one of the characteristics that defines a Mira variable.) Another way to detect a shock is to observe the velocity of the material ahead of the shock and behind it. We can measure those velocities very accurately by taking spectra and measuring the Doppler shift of the lines. In principle, at least, it is very easy.

A visual representation of the behavior of a Mira star atmosphere, based on theoretical computations, is shown in Figure 4. In this diagram, time goes horizontally, and the computed paths of individual particles are indicated by lines. The particles move like bouncing balls, and the shapes of these trajectories can be indicative of the surface gravity, $g = GM/R^2$. By comparing models such as this one with observed velocities we can (in principle, again) determine the gravity of the star.

So far such comparisons are showing that the gravity is higher than we had originally expected. This means either that the mass is larger or that the radius is smaller. It seems easier to fiddle with the radius, so we conclude that these stars seem to be smaller than we thought. It turns out that this is nearly equivalent to saying that the best radius is the smallest radius determined by other techniques, rather than the mean radius.

Higher gravity, or smaller radius, means that these stars are pulsating in the fundamental mode, whereas the previous measures that gave larger radii had suggested that they are pulsating in the first overtone. Perhaps the red semi-regular variables can now be understood as Mira-like stars that are pulsating in an overtone, giving them a shorter period.

Finally, our models show that the shock waves in Mira atmospheres are capable of driving mass off the star at such a high rate that it will remove the entire envelope in a few hundred thousand years. This is consistent with the best estimates of observed mass-loss rates -- 2×10^{-6} solar masses per year, give or take a factor of 10 -- determined for individual Mira stars. After the envelope is gone, the stellar core remains -- now, it is a typical white dwarf. Quite probably, some of the mass lost by the Mira in the last stages of its envelope shedding becomes a planetary nebula; this is a very transient object indeed, lasting only a few tens of thousands of years. So it may well be that mass-loss caused by Mira pulsation is what kills most stars, leaving nothing but a white dwarf (the core) and a temporary planetary nebula.

Figure 5 shows what you might see if you got up close to a Mira. It is a drawing, not a photograph, so take it with a grain of salt. We would see rising shocks heating the material and making it brighter (and bluer); there may be several of them visible at any given time.

To return to the question of why we are interested in these stars, the point is that with a variable star there are more measurable numbers with which to test the theories than there are with a static star. For example, the period and the visual amplitude will depend in some (complicated) way on the interior model, so you get some constraints on the theory by observing these stars. This in turn gives us clues to the chain of processes from star formation through mass loss and ejection into the interstellar medium and back to star formation. (I've sketched this cycle in Figure 6.) It now looks as though the Miras may, in fact, be very important in putting matter back into the interstellar medium.

Current models for these stars suggest that the past 75 years' data on Miras collected by the AAVSO span about half the time interval we need to actually see changes in their behavior resulting from mass-loss and evolution. So, please keep on observing the Miras!

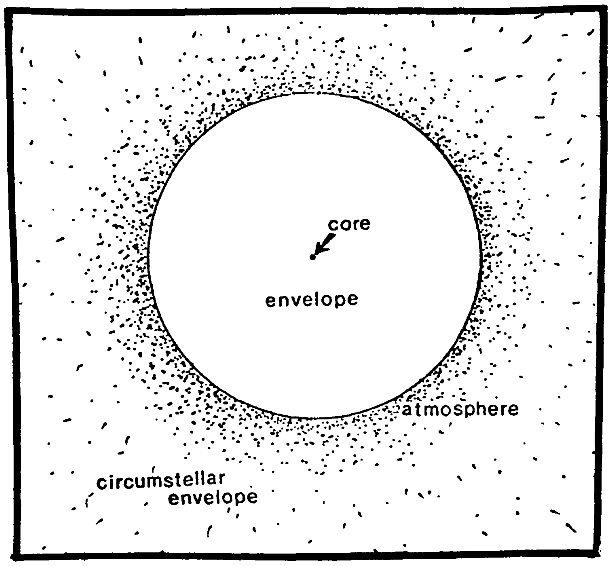

Figure 1. Important regions in a Mira star are sketched in this figure: the core, where nuclear reactions generate energy; the envelope, where energy is transported by convection and where the pulsations occur; the atmosphere, where the visible and infrared spectrum originates; the circumstellar envelope, formed by the flow of material away from the star.

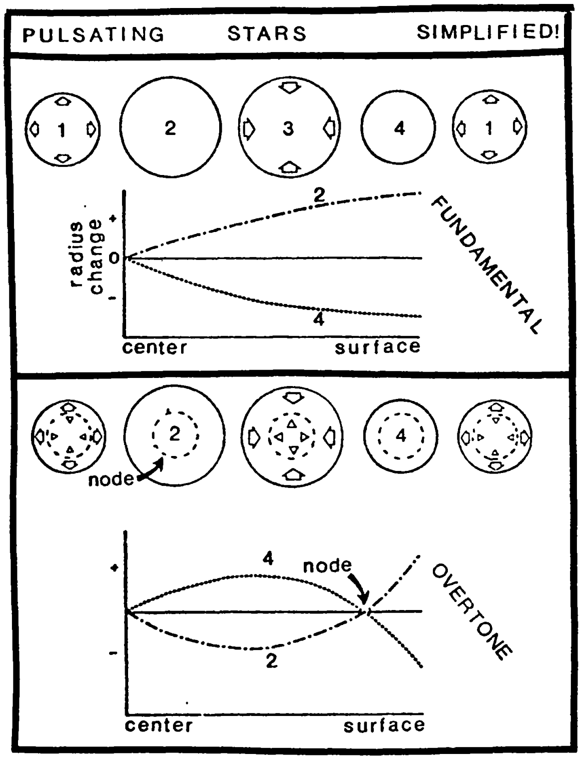

Figure 2. A simplified illustration of the properties of fundamental and first overtone modes in a star. The circles 1-2-3-4-1 show the size of the star at four times during its cycle; the arrows and triangles indicate the direction of the motion of the material in the star. Also shown is the deviation from the average position of particles inside the star at the time of maximum and minimum radius. The first overtone mode has one node, where the material does not move away from its equilibrium position during the cycle.

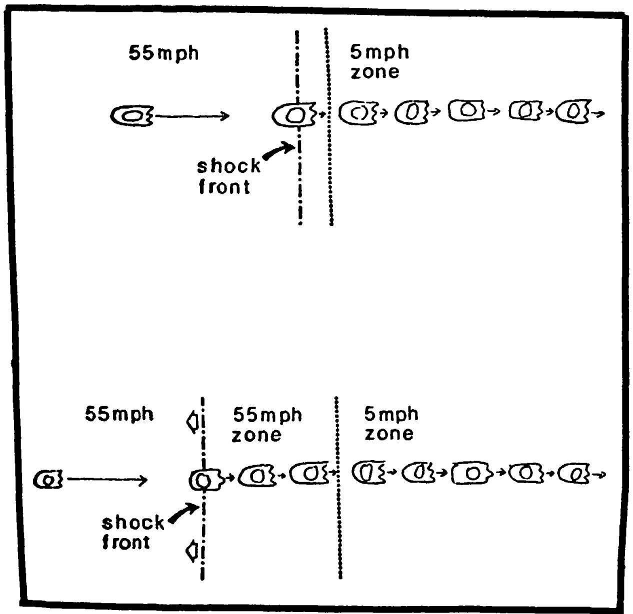

Figure 3. Traffic moving through a construction zone with a 5 mph speed limit on a highway with a 55 mph speed limit will form a standing shock if the cars are widely separated in the high speed zone (separation in car lengths greater than 55/5 -- upper illustration). If the separation is small, the "shock front" will propagate back into the high speed zone -- lower illustration.

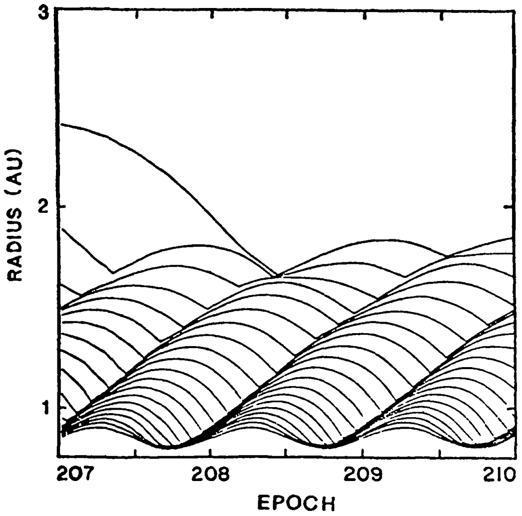

Figure 4. Computer-drawn illustration of the motion of particles in the atmosphere of a Mira. Where the motion changes abruptly from downward to upward there is a shock front moving through the atmosphere. The shape and amplitude of each trajectory are determined mainly by the gravity of the star; this is related to the behavior of a bouncing ball.

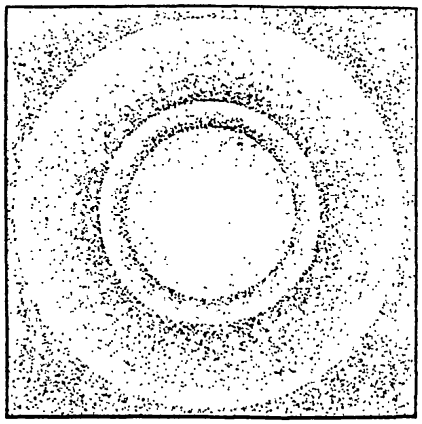

Figure 5. An illustration of what we might see if we could get close to a Mira: multiple bright shock waves rising through an atmosphere whose extent is comparable to the size of the star.

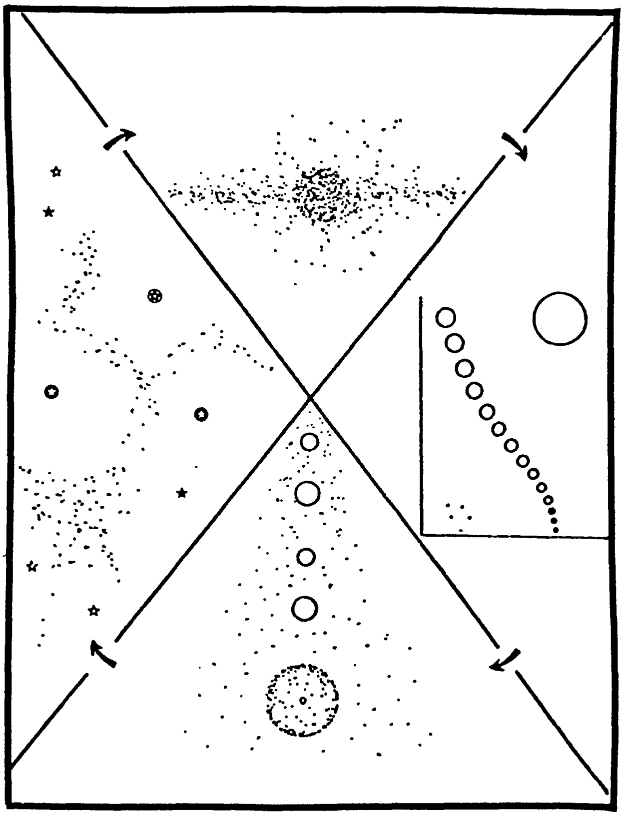

Figure 6. The material between the stars coalesces to form stars (top) which evolve through successive stages of nuclear reactions (right) until they reach the Mira stage, when large amplitude pulsation drives extensive mass loss and ultimately leads to the formation of a planetary nebula plus a white dwarf (bottom). The material ejected from the Mira replenishes the interstellar medium (left) and provides the substance for another round of star formation.