Not with a Bang but a Whimper

SUN KWOK, *Herzberg Institute of Astrophysics, Canada*

STARS do not live forever. What happens as they grow old? For a generation the picture has been one of violence, the details and degree of which vary from case to case. In this view, objects at least 1.4 times more massive than the Sun rush through a short, fierce life only to explode as supernovae, littering our galaxy with their debris. When this material dissipates all that remains — if anything — at the original site is a neutron star (perhaps detectable as a pulsar) or possibly a black hole.

Less massive bodies, such as our Sun, make a less dramatic exit. Until recently it was believed that they too came to a rather abrupt end, first bloating themselves into giants which vaporized and engulfed any planets in the vicinity, then ejecting their outer layers. The star creates its own tombstone in the form of a resultant planetary nebula, a glowing halo of matter which slowly expands and dims before fading away in some tens of thousands of years. The exposed core, meanwhile, shrinks to a hot white dwarf.

WHAT GOES SUPERNOVA?

These concepts of star death have remained popular for decades, as a glance at some elementary textbooks will show. But there are some uncomfortable facts to be faced. For example, supernovae are rather rare: no more than a few happen every century in our galaxy. This contrasts with the substantially larger number expected if every star of more than 1.4 solar masses becomes a supernova. A similar problem exists with pulsars: there ought to be more of them if the death of each massive star gives rise to one. Worse yet, the relatively young Pleiades cluster contains a white dwarf. This star must have descended from a progenitor of more than six solar masses; anything less implies a lifetime longer than that of the cluster itself.

Such problems have led to a growing conviction that conventional wisdom may be wrong here. In recent years more and more astronomers have adopted the view that only stars with masses more than eight times that of the Sun pass through the supernova stage and become neutron stars or black holes. The demise of less massive objects also may not be as abrupt as once thought. Their transitions to white dwarfs via the ejection of planetary nebulae may be a gradual, protracted process.

The best approach to the causes of star death is to examine the patient just before it expires — an "antemortem" of sorts. It is through research on red giants, the senior citizens among stars, that new ideas on this subject have gradually emerged.

What caused such a major shift of opinion was the discovery of strong radial stellar winds emanating from the surfaces of red giants. Such winds were first studied in 1956 by Armin Deutsch, utilizing spectra of Alpha Herculis taken in visible light. He found that several other cool, luminous stars exhibited the same behavior, but limited instrumental sensitivity prevented extension of the survey. Thus it was not clear at the time that stellar winds were occurring in all red giants.

Improved infrared and microwave radio technology in the 1960's permitted much more to be learned about such winds. Edward Ney and Neville Woolf detected infrared emission from dust grains mixed in the flows from most of the red giants they surveyed.

In general these stars are much brighter in the infrared than in the visible. Their shorter-wavelength radiation is absorbed by surrounding dust grains which then heat up and reradiate at longer wavelengths. One example is CW Leonis; the brightest source outside the solar system at five microns, it is barely detectable with large telescopes in the visible region of the spectrum. In some cases the winds are so strong, and contain so much material, that the stars themselves are totally obscured at visible wavelengths.

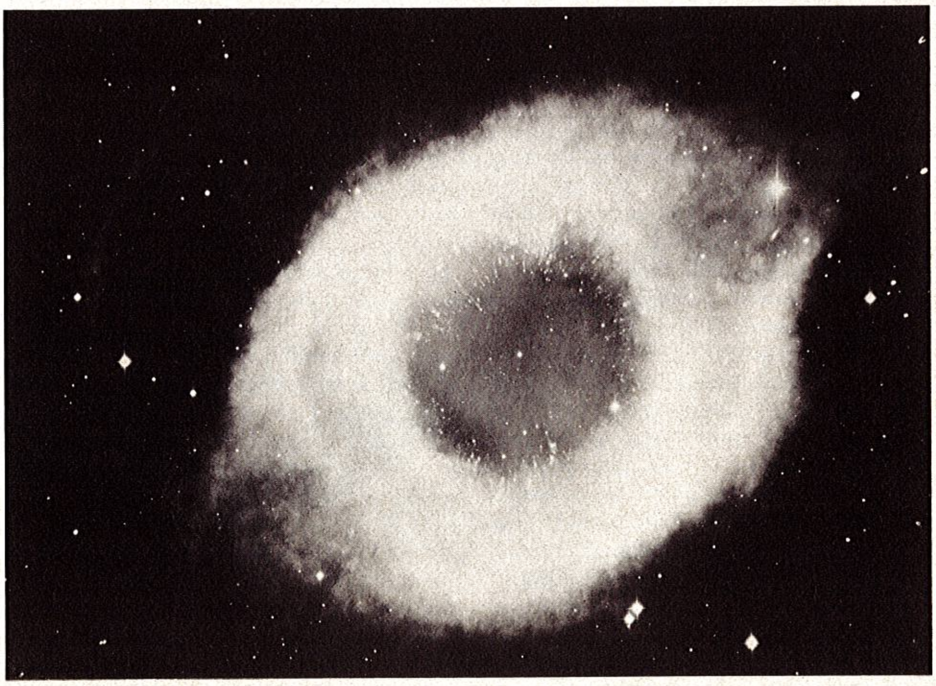
In the early 1970's radio emission lines from molecules (primarily OH, H_2O, and CO) were detected in the direction of old red giants. By the middle of the decade there was a consensus that this radiation also originates from stellar winds.

Use of these new observing tools soon made it apparent that almost all red giants in the galactic disk have stellar winds. Surveys in the infrared and the OH microwave radio line also uncovered many intrinsically bright red supergiants otherwise hidden by their dusty winds.

The amount of matter carried off the surface of a star by these winds is estimated to be as great as one solar mass every 100,000 years — fast enough to remove a large fraction of the star's mass in less than a million years, a very short time astronomically. In fact, calculations show that these rates far exceed those at which mass is consumed by internal nuclear burning, which had been thought to be the dominant physical process in stars.

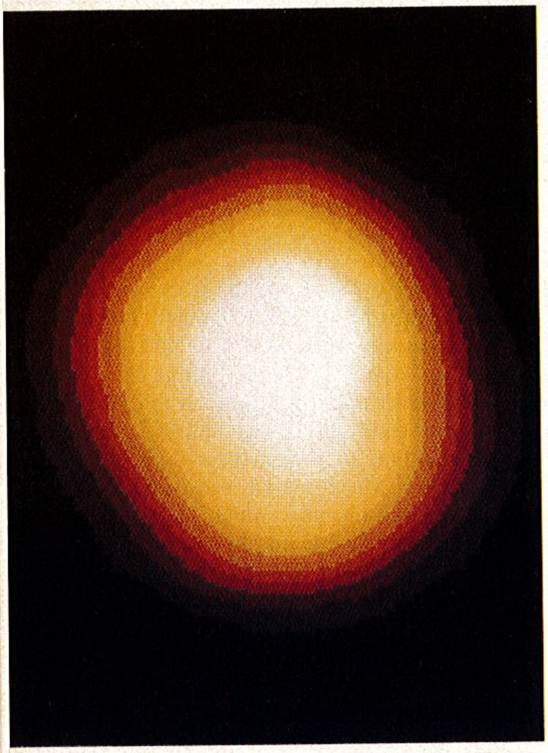
Considering the galaxy as a whole, these ejection rates imply that red giants, not supernovae, are the major "polluters" of the Milky Way. The former are in an advanced evolutionary state and have a high abundance of heavy elements synthesized internally and brought to their surfaces by convection. Their collective stellar wind is the dominant means of enriching the galaxy with the heavy elements incorporated in later generations of stars.

The observational case for winds from red giants is now very well documented. Obser-



NGC 7293, the Helix nebula, has strong atomic emission that renders it conspicuous in the visible region of the spectrum. However, the shell-like structure seen here represents only a brightness, or at most a density, distribution; it does not imply the absence of material outside and inside of the prominent features. The shell's appearance does not necessarily mean that all the matter in the planetary was ejected together from the central star. North is up in this photograph courtesy of Northwestern University.

vations of CO by Gillian Knapp and co-workers indicate halos as large as the one around the carbon star CW Leonis, which has an angular diameter of six arc minutes.



NGC 7027, as photographed in the red light of hydrogen-alpha and ionized-nitrogen emission by A. Condal, G. Fahlman, G. Walker, and J. Glaspey. It shows a faint halo spanning 30 arc seconds, roughly twice the size of this planetary's prominent shell. Courtesy G. Walker, University of British Columbia.

This cloud, a fifth the apparent size of the full Moon, corresponds to an actual extent 1,000 times that of the solar system! The halo contains no less than two solar masses of material; however, its density is not uniform but decreases outward from the star. (The solar wind, while similar in this respect, is about a billion times weaker and does not play a significant role in the evolution of our star.)

The high resolution of the Very Large Array radio interferometer has permitted the direct measurement of similar features elsewhere, while sensitive new detectors used by Andrew Bernat and others at Kitt Peak National Observatory have revealed a halo around Betelgeuse extending 1.5 arc minutes from the star. While we must still rely on the indirect methods of spectral analysis to study more distant objects, these direct "photographs" of stellar halos greatly consolidate the case for mass loss from red giants.

WHITE DWARF, NEUTRON STAR, OR BLACK HOLE?

Although heated debate still rages on the causes and evolution of stellar winds, most workers in the field would probably agree that the rate of mass loss increases with age. Further, it seems likely that a star of eight solar masses can lose enough material this way to drop below the critical limit of 1.4 solar masses for white-dwarf formation before it dies.

This period in the life of a star is therefore a fierce race between nuclear "burning" at its center and wind ejection from its surface. If enough "ashes" from the former can accumulate, then a supernova can be triggered. On the other hand, if enough fuel can be removed before the critical mass is reached, there will be no titanic explosion.

Since most stars in our galaxy are born with masses far less than eight Suns, ejection of matter by strong winds from red giants makes supernovae (at least those of Type II) rare. Perhaps five percent of all stars end their lives in such a spectacular manner; most merely become white dwarfs. This means that the production of neutron stars and, in particular, black holes is far less efficient than previously thought.

WINDS AND PLANETARY NEBULAE

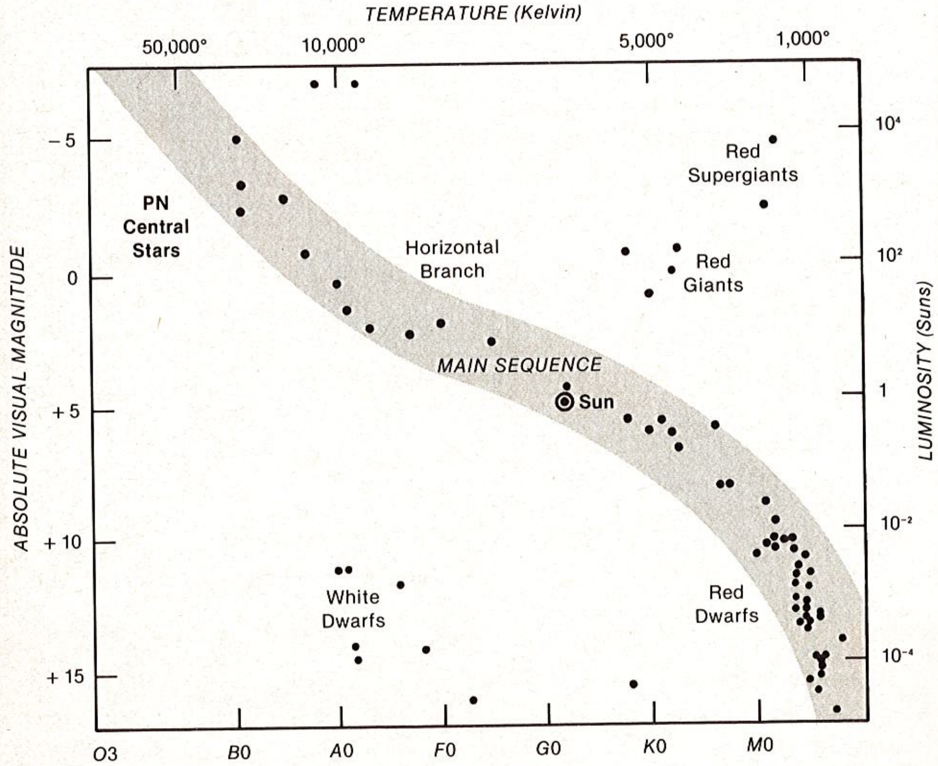
The discovery of massive winds from red giants presented new problems concerning the origin of planetary nebulae (see page 129 of the February issue). It has been commonly assumed for some time that planetaries result from the abrupt ejection of the outer layers of a red giant. Typically, the observed masses of such nebulae are about one tenth that of the Sun, small compared to the material lost through stellar winds.

If every planetary is descended from a red giant, each should be surrounded by a massive invisible halo previously produced by the stellar wind. The question of possible relationships between these two circumstellar components was raised in a 1978 paper by Christopher Purton, M. Pim Fitzgerald, and me. Since the mass of a planetary is so low, it can be created by redistributing the wind-ejected material. The means we proposed to accomplish this rearrangement can be called the "snowplow" process.

A red giant consists of a hot dense core and a cool tenuous envelope, and we argued that the wind continues until that core is exposed. The resulting color change of the star from red to ultraviolet will increase the wind's speed from about 10 to around 1,000 km per second. This new fast wind will push against the old slow wind like a snowplow, piling up high-density material at their interface.

Strong atomic emissions produced in the dense region make the swept-up material visible, while strong pressures inside and out form a thick shell that to us appears ring-shaped. We calculated that, after a few thousand years, the expansion velocity, size, density, and mass of such a structure would all be similar to those observed for a typical planetary. Note that, in this theory, the mass of the nebula is not constant, but increases with time. A recent study by Stuart Pottasch has shown that the masses of these nebulae increase linearly with increasing size, in accord with our picture.

The snowplow and conventional sudden-ejection theories differ in that the former predicts the presence of material both inside and outside the nebular shell. Thus, detection of such low-surface-brightness material is essential for the new picture. Recent advances in instrumental sensitivity and spectral coverage have made observational tests



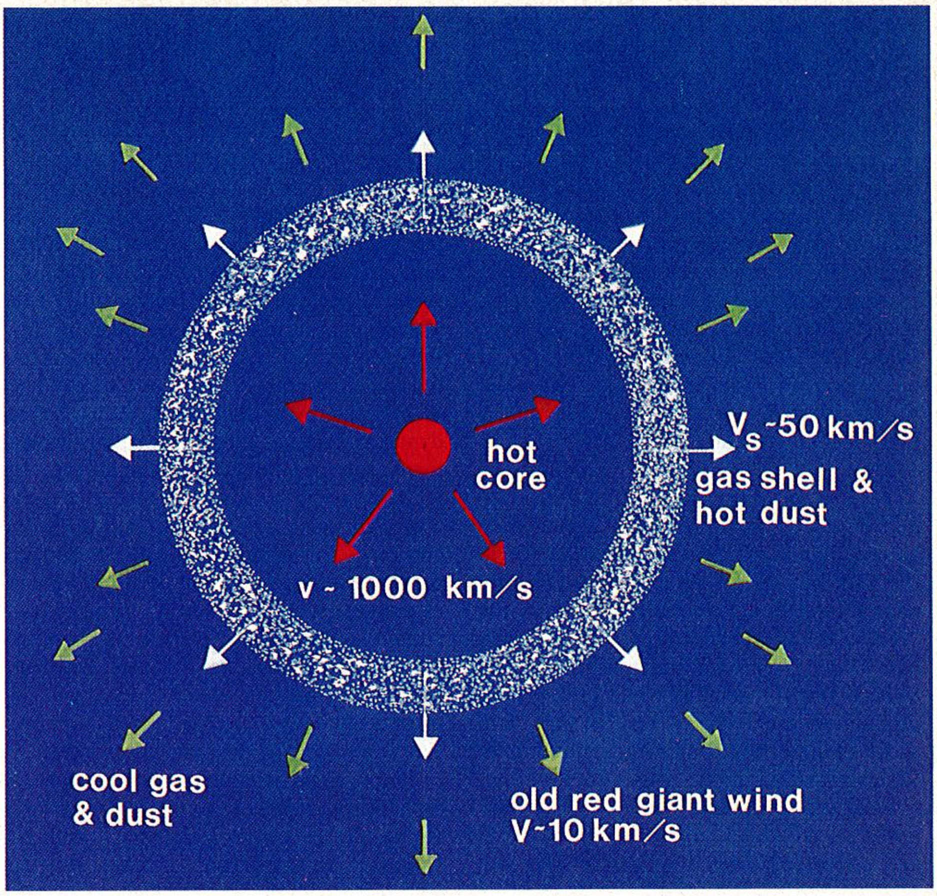
Planetary nebula precursors (giants and supergiants), central stars, and end products (white dwarfs) are marked on this Hertzsprung-Russell diagram.

possible, and faint halos have indeed been found to surround planetaries.

Optical detectors with extended dynamic range have been employed by groups at the University of British Columbia and Imperial College, London, to reveal faint halos several times the size of the nebular shell in the planetary NGC 7027, as shown in the photograph at left. In addition, observations with the International Ultraviolet Explorer satellite by Sara Heap and others provide evidence of fast winds emanating from the central stars of planetaries. These results support the suggestion that ejection is not an isolated phenomenon, but may be dynamically affected by stellar winds.

Although we are reasonably certain that winds play a role in the formation of planetary nebulae, can we be sure that sudden ejection never occurs? It is commonly thought that, when a star gets old, it becomes restless, pulsates a little, and finally erupts in some way. While pulsating (this interval is called the Mira phase after the famous variable), the period is thought to increase with age.

It was once believed that a star's life as a red giant ended in a more or less violent ejection of material when the period reached 400 to 600 days. Recently, however, Miras with periods as long as 2,000 days have been detected with the Dwingeloo, Holland, radio telescope. Such stars were previously unknown because they generate such strong winds that their study at visible wavelengths is impossible. The existence of such objects shows that stars of extremely advanced age still can have winds (and very strong ones), thus greatly diminishing confidence in the "sudden-death" scenario.



This schematic diagram illustrates the "snowplow" model of planetary nebula formation. The green arrows represent the remnant low-speed stellar wind ejected during the previous red-giant phase, while the red arrows show the newly developed fast wind from the recently exposed hot core of the giant. The white material is the high-density pileup of gas at the interface of the two winds, which we observe as a planetary. Courtesy Sun Kwok.

SUMMING UP

Our ideas concerning the later stages of stellar evolution have undergone a quiet revolution in the last decade. We now know that wind-driven mass loss is as important as nuclear burning in controlling the development of red giants, and the number of stars that become supernovae seems to be considerably fewer than previously believed. The great majority, which do not expire catastrophically, may take a less violent route to the planetary nebula stage than once thought. Extremely violent processes, appealing as they might be, may have to give way in the face of new observations.

Unlike old soldiers, old stars do die. But, like them, most may just quietly fade away.

REFERENCES

This subject is also treated in my article "Star Dust, Mass Loss and the Late Stages of Stellar Evolution," in the *Journal* of the Royal Astronomical Society of Canada, Vol. 74, 216-233, 1980. A recent review by B. Zuckerman, "Envelopes Around Late-type Giant Stars," appeared in *Annual Review of Astronomy and Astrophysics*, Vol. 18, 263-288, 1980, while the late B. Tinsley discussed "What Stars Become Supernovae" in the *Publications* of the Astronomical Society of the Pacific, Vol. 87, 837-848, 1975.

RED GIANTS AS MOLECULE FACTORIES

Hydroxyl (OH) was the first molecule associated with stars to be detected in the microwave radio spectrum. Its discovery in 1968 began a new era in stellar spectroscopy and has led to the discovery of at least 18 others to date. The observation, at so early a stage in the development of microwave technology, was possible only because this molecule acts as a maser and has extremely strong emission at a wavelength of 18 cm. Later, improved detectors made possible observations of the first nonmasering molecule, carbon monoxide (CO), produced in great abundance by red giants.

Interferometry with very long baselines determined that maser emissions are associated with stars but left the exact relationship unclear. Theoretical analysis of the observed spectra, however, demonstrated that the molecular emission originated in a steady stellar wind.

In the years since, increasingly complex molecules have been found to be manufactured by red giants and ejected into interstellar space. The 13-atom organic substance $HC_{11}N$, which has a molecular weight comparable to that of amino acids, was detected recently. (See page 455.)

Just how these complex molecules are produced is not known. Red giants, however, are a preferred location of origin: such stars in an advanced stage of development provide the necessary heavy elements, produced by nuclear processes in their interiors, as well as a low-temperature environment favorable to molecular formation. Carbon stars, which are believed to be very highly evolved red giants, are observed (not surprisingly) to make the largest variety of organic substances. The measured wind velocities imply that the observed molecules must have been synthesized within the last few hundred years.

Studies of red-giant winds provide us with the only direct evidence for the synthesis of complex molecules in space. Additional improvements in instrumentation conceivably could lead to the detection of substances of considerable biological importance. These molecules may be unobservable at present only because of their complex structure, not necessarily due to their rarity.

Winds from red giants not only may be important in the evolution of stars, but also may have significant implications for the biochemical evolution of our galaxy.