lorimeters for analyzing jets, and new devices for particle identification.

The energy-luminosity question also affects the choice of future particle facilities. The lepton colliders have much higher ratios of event cross section to total cross section and thus permit cleaner experiments and more precise tests. However, lepton colliders may be restricted from attaining the high energies available in hadron colliders. On the other side of the coin, the costs of building p–p colliders rise rapidly with energy. Accelerators with $\bar{p}$–p colliding beams may reduce costs but at a sacrifice in luminosity. The structure of the machine—the number of interactions, the addition of more rings—may alter these tradeoffs in one way or another. —BGL

Theory points to pulsating white dwarfs

Astronomy is, in a fundamental sense, an observational science. Unlike some areas of modern physics, for example, where theoretical developments are often the driving force behind experimental progress, new discoveries in astronomy most often spring from new instrumentation for the observer; theoretical predictions of yet-to-be observed phenomena are rare.

An elegant exception to this rule has recently emerged from the study of white dwarf stars. Rapid development in the theory of pulsating white dwarfs over the past three years led to the publication[1] early last year of a prediction of a new class of variable stars. A few months later, an object matching the theoretical description was found. Donald Winget, whose dissertation research at the University of Rochester formed the basis of the prediction and who was part of the observing team at the University of Texas where the new star was found, told us, "This is the first instance in which the existence of a new type of variable star was predicted from theoretical considerations." His thesis adviser, Hugh Van Horn, added that the new star's discovery "provides an important confirmation of the underlying theory of pulsating white dwarfs."

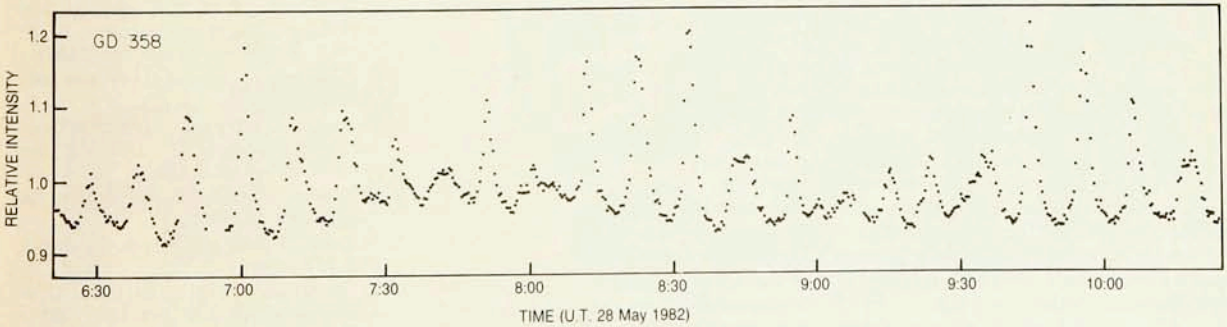
The white dwarf phase is the final state for most of the stars in the universe (PHYSICS TODAY, January 1979, page 23). With its supply of nuclear fuel exhausted, a star will begin to contract. For stars with masses less than a few times that of the Sun, the stellar envelope is subsequently ejected, and the central contraction is stopped by electron degeneracy pressure before the core temperature becomes high enough to initiate the next set of fusion reactions. The result is a solar-mass star with a radius comparable to that of the Earth and a mean density of about 10^6 gm/cm^3; most of the star's mass is contained in a degenerate carbon core. Roughly 80% of known white dwarfs have spectra showing an overlying atmosphere of pure hydrogen, whereas most of the remainder exhibit only helium lines. The origin of the distinction between these so-called DA and DB dwarfs is not well understood.

With gravitational contraction prevented by the pressure of the degenerate Fermi gas and a central temperature too low for exothermic nuclear reactions to proceed, the only energy reservoir remaining is the thermal energy content of the star. From an initial blackbody temperature larger than 10^5 K, the temperature and luminosity of the star decline monotonically as the heat is gradually radiated away. Recent theoretical cooling calculations suggest that the star will reach a surface temperature of about 5000 K in $5–7\times10^9$ yr; the coolest white dwarfs known are at about this temperature. The current population of white dwarfs, then, may be viewed as a fossil record of the entire history of star formation in the Galaxy.

In 1968, the discovery of quasi-periodic (with a period of about 750 sec) light variations in the white dwarf HL Tau-76 by Arlo Landolt (Louisiana State University) stimulated a number of observers to search for other examples. An extensive survey by James Hesser and Barry Lasker at the Cerro Tololo Interamerican Observatory in Chile uncovered the white dwarf pulsator ZZ Ceti after which this class of stars has been named. Others of the 16 stars found to date were detected by Brian Warner (now at the Capetown Observatory) and Edward Robinson (University of Texas) and John McGraw (University of Arizona).

All stars have hydrogen envelopes (type DA), and all are multiperiodic, with as many as six or more separate frequencies apparent in their light-curve power spectra. The low-amplitude pulsations have remarkably stable periods, with upper limits to a period derivative $\dot{P}$ as low as 6×10^{-14} sec/sec. Perhaps the most remarkable aspect of the stars, however, is their temperature distribution: Despite the large range of known white dwarf temperatures (5000–100 000 K), all of the pulsating stars lie in the range 11 000–13 000 K. Furthermore, recent studies of large samples of pulsating and nonpulsating dwarfs by Jesse Greenstein[2] (Caltech) and Gilles Fontaine, Pierre Lacombe (University of Montreal), McGraw, David Dearborne and J. Gustafson[3] (University of Arizona) conclude that most, and possibly all DA stars in this temperature range pulsate. One is thus forced to a single-parameter model in which every white dwarf starts oscillating when it cools to 13 000 K and stops again after cooling another 10%.

One question that must be addressed in the pursuit of such a model is the identification of the modes of oscillation these stars undergo. Simple radial pulsations (such as those seen in classical Cepheids and RR Lyrae variables) are ruled out; spherically symmetric radial oscillations of a white dwarf have periods on the order of the time



The light curve of the helium white dwarf variable GD 358 showing the complex multiperiodic behavior characteristic of nonradial pulsators. A total of 29 oscillation modes with periods ranging from 142 sec to 952 sec can be indentified from an analysis of this light curve. (From ref. 7.)

for sound to cross the star (about 1 sec), two to three orders of magnitude shorter than the observed range for ZZ Ceti stars. Departure of a star's density distribution from spherical symmetry during oscillation, however, brings a change in the frequencies excited and a new set of nonradial modes, dependent on the density gradient in the star, can become important. The well-known five-minute oscillations in the Sun reported by Henry Hill and his collaborators at the University of Arizona (PHYSICS TODAY, May 1976, page 17; see also the article by Gordon Newkirk Jr and Kendrick Frazier, PHYSICS TODAY, April 1982, page 25) are thought to be overtones of these "*g*-mode" pulsations. As originally pointed out by Yoji Osaki (University of Tokyo) and Carl Hansen (Joint Institute for Laboratory Astrophysics), the expected *g*-mode periods and period ratios for a white dwarf match those observed in ZZ Ceti stars.

The next important question is the driving mechanism for the oscillations. For most stars, the opacity of the envelope is proportional to $\rho^r T^{-s}$ where both r and s are positive exponents (that is, the optical depth to outflowing radiation increases with increasing density ρ and decreases with increasing temperature T). In the zone where a dominant element is undergoing ionization, however, s changes sign: Owing to the energy absorbed by ionization, the opacity *increases* with temperature. Thus, the star is hottest (high T) when in a contracted (high ρ) state which leads to expansion of the envelope; following expansion (lower ρ) the star cools (lower T), and the outer layers fall back. A small perturbation from equilibrium, then, will result in an oscillation driven by this ionization/opacity effect.

In 1979 Hill organized a meeting in Tucson on nonlinear and nonradial stellar pulsations. Van Horn told us the meeting served as an important "trigger" to the recent rapid advances made in applying the theory of nonradial stellar pulsations to white dwarfs. In 1977 Wojciech Dziembowski of the Nicolaus Copernicus Astronomical Center in Warsaw had published calculations outlining a promising method of attack (which he reported at the Tucson meeting) and pointed out the importance of nonadiabatic processes in the white dwarf atmosphere. Gerard Vauclair of Meudon (though not present at the meeting) had been pressing for a realistic treatment of element stratification, which arises from the strong gravitational field (g on the order of 10^8 cm/sec^2) in the outer layers of the stars, while the Rochester group contributed their detailed models of white-dwarf stellar evolution.

Following the meeting, the three groups embarked on independent studies of the expected oscillation spectra for compositionally stratified white dwarfs. Their results, all published[4,5,6] within the last year, represent a major advance in our understanding of the ZZ Ceti phenomenon, and hold important implications for the general problems of white-dwarf physics and stellar evolution. The most recent theoretical work, done by Winget, Van Horn, Monique Tassoul (Montreal), Hansen, Fontaine and Bradley Carroll (Joint Institute for Laboratory Astrophysics)[1], includes models that reproduce the observed periods and spectra of the oscillations, as well as the temperature range within which the instability should occur. In addition, growth rates for the various eigenmodes have been calculated, and the authors find encouraging agreement with increases in the amplitude of the light fluctuations, which have been observed on a timescale of months.

Winget and his collaborators also investigated the importance of the thickness and depth of the ionization layer in the star's hydrogen atmosphere, which determines the temperature range in which pulsations will occur and selects the modes that are excited. The variation of the depth of the hydrogen-driving region with temperature suggested that similar oscillations could be excited in a deeper helium zone at a higher temperature. A search of the model's parameter space strongly suggested a second narrow instability regime for stars with zero hydrogen abundances and temperatures of 20 000–30 000 K. The authors conclude, "We also expect that variable DB white dwarfs should exist in this T range . . ." as a result of an instability driven by helium ionization.

Upon receiving his degree in September 1981, Winget went to Texas as a postdoctoral fellow at the McDonald Observatory and convinced his new colleagues to undertake a search for oscillating helium white dwarfs. Only about 60 DB stars are known, and only a handful of these should lie in the temperature range of the predicted variability. About halfway through a systematic search of the entire sample, however, Winget and his collaborators (Robinson, Fontaine and R. Edward Nather) scored a hit with the star GD358 in which several periods ranging from 140 sec to 950 sec were detected.[7] The temperatures of DB dwarfs are much more difficult to determine than those of their hydrogen counterparts, but Winget told us that a spectrum recently obtained by Vauclair with the International Ultraviolet Explorer satellite was consistent with a temperature of roughly 30 000 K. Most of the other stars observed to date had temperatures less than this and were not variable. Thus, not only does the star within the theoretical instability region pulsate, but the stars outside this temperature range are stable, as predicted. Future observations are expected to concentrate on increasing the size of the sample and the reliability of the DB temperature scale so that more "GD358" variables can be located.

Confidence in the theory of white-dwarf pulsations has been bolstered by the discovery, and astronomers are looking forward to using these variable stars as a "laboratory" in which to explore a number of problems concerning the structure and evolution of white dwarfs. For example, the rotation periods of these stars are notoriously difficult to determine; line splitting in the Fourier components of the light-curve power spectra of ZZ Ceti stars has been used to estimate periods in the range of 30 minutes to 1 day in four objects. In addition, the period derivatives of the *g*-modes can be directly related to the cooling rate for the stars, something that, to date, has only been calculated theoretically and about which there is considerable disagreement. A measurement of $\dot{P}$, possible within a decade, would yield important insights into the physics of the white-dwarf interior, as well as allowing the direct transformation of the white-dwarf luminosity function into a history of the star-formation rate in the Milky Way. Bohdan Paczynski (at Princeton, on leave from the Copernicus Center) cited another important problem to be addressed with the new theoretical models. The outer layers of the predwarf stars are predominantly hydrogen, yet the thickness of the hydrogen layer for DA dwarfs required to match the observations corresponds to a mass of only 10^{-8} to 10^{-12} solar masses. Paczynski asks, "How can the hydrogen atmosphere be so thoroughly removed?" The answer will reveal much about pre-white dwarf stellar evolution, the structure of DA and DB stellar atmospheres and the possible existence of hot coronas, as well as about the subsequent evolution of these dying stars, our most direct link to the early history of the Galaxy.

—DAVID HELFAND

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