Jesse Greenstein (right) welcomes Willy Fowler to the symposium on low-luminosity stars.

Some Faint Stars and a Bright One

by Virginia Trimble and Judith G. Cohen

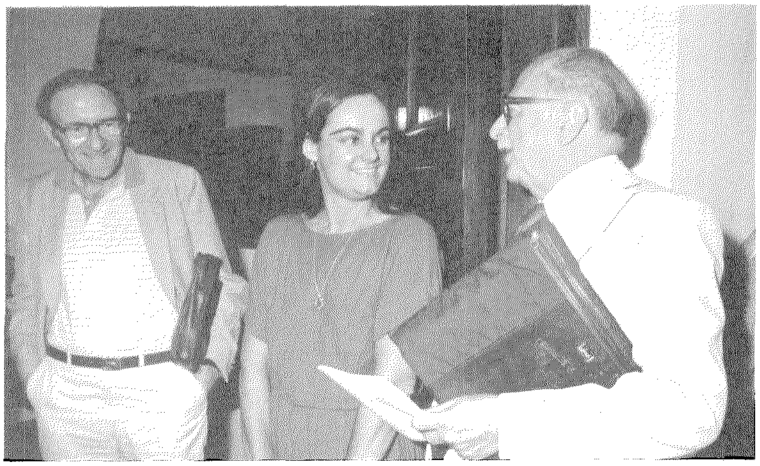
THE LOW-LUMINOSITY STARS are a wild assortment — hot and cool, old and young, dense and diffuse — almost as motley a crew as the 85 astronomers who gathered at Caltech on October 15-16, 1984 to discuss them and to honor the 75th birthday of Jesse L. Greenstein, the DuBridge Professor of Astrophysics, Emeritus, a pioneer in the study of faint stars, especially white dwarfs. The faint stars include both the small, low-mass subset of normal, hydrogen-burning stars, as well as the corpses of more massive ones that have essentially completed their nuclear reactions.

Inevitably, low-luminosity stars are not individually spectacular (not one is a naked-eye object), but they are astronomically interesting nonetheless. Low-mass stars are extremely numerous and collectively have a major fraction of the total stellar mass of our galaxy. Just how large a fraction is currently much debated. The compositions of the remnants of massive stars tell us about the nuclear processes that gradually transformed a few percent of the galactic mass from hydrogen and helium into the heavier elements found in the earth and in ourselves. These remnants are sometimes called degenerate dwarfs; they are so dense that their interiors are degenerate (this is a statement about the electron velocity distribution, not their moral principles). They thus provide a laboratory for studying physical conditions we cannot replicate on earth. And the faint stars are the longest lived of all, providing a probe of star formation in the distant past. In fact, as Greenstein noted at a 1968 meeting on the same subject, the astronomers who study faint stars will inherit the skies by default after 10^{11} years.

In the meantime, some of the issues on which participants at the October conference had recent progress to report included magnetic fields on the surfaces of some white dwarfs (stronger than any ever produced in terrestrial laboratories); the existence and modeling of a new class of pulsating, hot subdwarfs; and the interpretation of white dwarf compositions.

The magnetic field at the surface of the earth has a strength of less than one gauss; a household magnet measures about 100 gauss; and the strongest fields produced in the laboratory for research purposes (over very small volumes and very briefly) can read just about a million gauss. Thus the discovery about 15 years ago of circular polarization, implying a field of at least 100 million gauss on the surface of one white dwarf, made it immediately clear that we were seeing a new physical regime. The particular star involved (Greenwich +70°8247) was already famous for having absorption lines in its spectrum that had defied interpretation since Rudolph Minkowski first photographed them at Mt. Wilson in 1939.

The report of the strong field quickly triggered a flurry of papers attempting to identify the lines. The basic idea is that strong magnetic fields grossly perturb electron orbits, so that spectral lines split into many components, shifted by different amounts from their normal wavelengths. Some suggestions were intriguing (transitions in unbound He_2 molecules for instance), but none matched the observed lines well or obtained general acceptance. Sufficiently accurate quantum-mechanical calculations of the expected wavelengths were difficult, and there could be no laboratory data to check against. Another problem was that the wavelength shifts change sharply with field strength, so that variations in field in the star's atmosphere



Virginia Trimble contemplates suitable forms of birthday greetings for Greenstein with assistance from Robert O'Connell (Louisiana State University).

would smear features beyond detectability.

Two recent developments have finally sorted out the mess. The first was Greenstein's detection in 1983 of an ultraviolet line in the spectrum of Grw +70°8247, which he attributed to the simplest of all atomic transitions (ground state to first excited state in hydrogen, called Lyman alpha). Thus the calculations became more tractable. The second was the development of the idea of stationary components, lines whose wavelength stays nearly constant over a range of field values (owing to a turning point or inflection point in λ vs. B). This permits absorption to be concentrated in a single, narrow wavelength band over the whole stellar surface.

Observers Roger Angel (Steward Observatory of the University of Arizona) and Jesse Greenstein (Caltech), and theorists R. F. Henry and Robert O'Connell (Louisiana State University), and G. Wunner (Tübingen) were, therefore, able to report general agreement in attributing both optical and ultraviolet lines in Grw +70°8247 to transitions in the most common element, hydrogen. These lines include components of Lyman alpha and of Balmer alpha and beta, some never seen in the laboratory, because they exist only in the presence of a strong magnetic field. The surface field for Grw +70°8247 is in the range 2-6 x 10^8 gauss. Because of the stationary line concept, it cannot be determined exactly, but a mystery nearly 50 years old was solved.

Several other stars with unusual absorption spectra are currently under study and may also have fields in the range 10^8-10^9 gauss. For fields above 2 x 10^9 gauss, the normal hydrogen lines all move into the ultraviolet, and will typically not be seen. A few such stars could conceivably be hiding among those (called DC) that display no visible lines.

Stars whose brightness varies because of periodic changes in size or shape have been known for more than a century and have been understood since the 1920s. Such pulsational variables include the Cepheids, classic indicators of the cosmic distance scale. For most pulsating stars the driving force is a zone just below the surface in which hydrogen is partially ionized. The zone acts as a sort of faucet, letting light and heat leak out when the star is expanded and bottling them up when it is compressed. Such stars necessarily occur over a fairly narrow range of surface temperatures, just below the temperature at which hydrogen ionizes. They are particularly valuable astronomical tools because the periods, amplitudes, and shapes of the pulsation curves are sensitive to the distribution of density and composition inside the stars. Thus we are able to probe the density and composition in the invisible stellar interiors in addition to measuring total masses.

The white dwarf variables are called ZZ Ceti stars. They show normal (for white dwarfs) atmospheres of pure hydrogen and have surface temperatures near 12,000K and pulsation periods of 200-1,200 seconds. These can be modeled as shape distortions, driven by hydrogen ionization and restored by gravitation (called non-radial g modes). The surprise is that detailed matching of the driving force with pulsational properties requires that the hydrogen atmosphere be exceedingly thin, only about 10^{-7} of the total stellar mass. It is very difficult to get a star to burn or eject all of its hydrogen this efficiently.

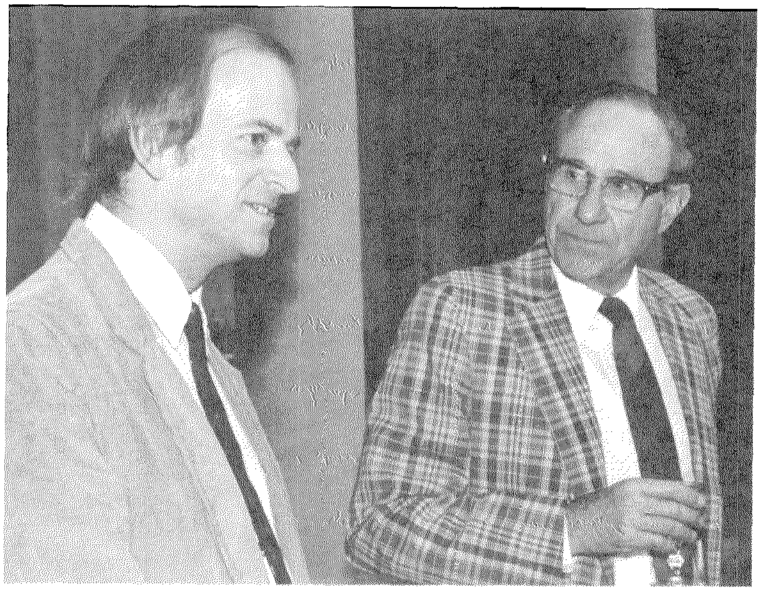
Georges Michaud (PhD Caltech 1970; University of Montreal) reported that this can be done via a new physical process — diffusive hydrogen burning, which is described later in this article — while Icko Iben, Jr. (University of Illinois) believes it to be quite impossible. Even with the new process included, his thinnest hydrogen layers are more like 10^{-4} of the mass of the star. An important difference between the calculations is the thickness of the helium layer intervening between the hydrogen envelope and the carbon-oxygen core where hydrogen can be burned. This and other disagreements between groups working on the problem remain to be sorted out.

A second class of pulsating white dwarfs, with higher temperatures and nearly pure helium atmospheres, is driven by a helium ionization zone and does not seem to present any special problems.

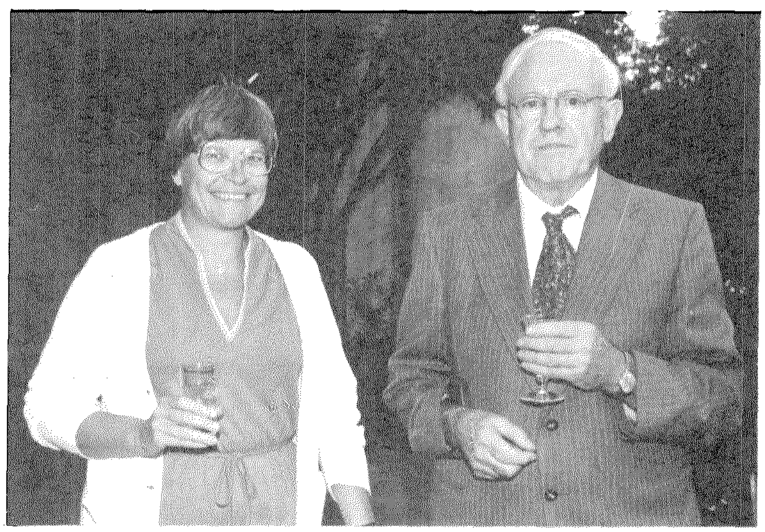
Most of the excitement centered around a new third class, one of whose four members has just ejected its outer layers in a planetary nebula and so must have completed nuclear reactions very recently indeed. These stars have surface temperatures of 100,000K or more, arguably the highest known for any sort of star, and their spectra show lines of helium, carbon, and oxygen. The class is named for its prototype, PG 1159-035 from the Palomar survey carried out as part of his dissertation by Richard Green (PhD Caltech 1977).

Two surprises about this new class surfaced. First, Donald E. Winget (University of Texas, Austin) reported that the pulsation period of PG 1159 is dropping at a rate of about 10^{-11} sec/sec, corresponding to an evolutionary time scale of only about a million years. Contraction of the star should make the period shorter, and cooling should make it longer. Thus the former must be more important right now. There will soon be more data on this star and other members of its class. Comparison of these with the pulsation calculations and evolutionary models should tell us the masses of the stars (probably larger than the general run of white dwarfs, according to James Liebert of Steward Observatory) and the rate at which they are cooling (hence the extent to which nuclear reactions are still contributing to their luminosity).

The second surprise, reported by Sumner Starrfield (Arizona State University), is that the pulsation properties of PG 1159 and of the pulsating planetary nebula nucleus K 1-16 require a composition that is about half oxygen (and the other half mostly carbon) almost to the very surface of the star. The stars must have been extremely efficient at getting rid of their hydrogen and helium envelopes, because the progenitors of white dwarfs (stars two to five times the size of the sun) have generally been thought to produce little oxygen. The burning of helium produces both carbon and oxygen in a ratio that rises with the temperature at which burning occurs. Greenstein expressed some skepticism that the requisite oxygen abundance could be produced in relatively cool, low-mass stars. William A. Fowler, Institute Professor of Physics, Emeritus, reminded the participants that a recent Kellogg remeasurement of the cross section for the reaction $C^{12}(\alpha,\gamma)O^{16}$ yielded a value about three times the previous one, thereby



Preparing for a birthday toast at the Athenaeum are Jeremy Mould and Marshall Cohen (above); Richard Green (Caltech PhD 1977), now at Kitt Peak National Observatory, and Judith Cohen (middle); and long-time friends and colleagues Anne Merchant Boesgaard (Hawaii) and Lawrence Aller (UCLA) in the bottom photo. Mould, Cohen, and Cohen organized the conference.



enhancing the oxygen/carbon ratio in the end-products of helium burning. Perhaps the PG 1159 stars are independent confirmation of the laboratory result.

Most degenerate dwarfs show strong spectral lines of only one element — hydrogen or helium or carbon. This has been understood to first order since 1945, when Evry Schatzman (Paris) pointed out that their very strong gravitational fields would force the lightest element present to float to the top in much less time than the stars take to evolve.

A few white dwarfs show hydrogen plus helium or some heavier elements — carbon, calcium, and magnesium are typical. They too are comprehensible, the surface abundances reflecting a combination of the accretion of fresh material (from surrounding interstellar gas or the wind of a companion) with Schatzman's gravitational settling and radiation pressure. Gary Wegner (Dartmouth) discussed a third group in which nearly pure helium atmospheres harbor some carbon (less than we see in the sun but more than should have survived gravitational settling). He pointed out that these stars have just the surface temperatures where currents of rising and falling gas should penetrate deepest into the star, dredging up material from the heavy-element-rich interior. And, as we saw a couple of paragraphs back, we expect the interiors of white dwarfs to be at least half carbon.

The really difficult case consists of the few stars with helium atmospheres contaminated by elements heaver than carbon (again, less than we see in the sun but more than should have survived settling). If the explanation is dredge-up, then nuclear reactions in the parent stars must have proceeded much further than we think they can in the sorts of stars that make white dwarfs. And if accreted interstellar gas is to blame for heavy elements, then where has the dominant hydrogen gone?

Michaud described a rather curious process that may provide the answer. Gravitational effects are trying to float any available hydrogen atop everything else. But there will be an exponentially decreasing tail of hydrogen concentration down into the star. For surface temperatures between about 10,000K and 30,000K, this tail penetrates into carbon-rich regions hot and dense enough for hydrogen to burn by the carbon-nitrogen-oxygen cycle. So efficient is the burning that it tries to establish an equilibrium hydrogen concentration even smaller than the exponential tail provides. Thus hydrogen continuously diffuses down and burns as fast as it accretes, leaving the atmospheric abundance below detectability. While gravitation tugs downward on the accreted metals, enough atoms pass through the atmosphere at any given time to make the lines we see.

Diffusive hydrogen burning therefore enables us to understand an otherwise incomprehensible mixture of elements in white dwarf atmospheres. It apparently solves two other problems as well. The first is the thinness of the hydrogen layer in the pulsating ZZ Ceti stars discussed above. The second is a gradual evolution from hydrogen-rich to helium-rich atmospheres as white dwarfs age. Since these stars have no internal nuclear energy sources, the oldest are necessarily the coolest and faintest. Greenstein's most recent compilations of Palomar white dwarf spectra show that the ratio of hydrogen-rich to helium-rich stars drops from 4:1 among the hottest to 0.5:1 among the coolest. It seems that diffusive hydrogen burning consumes enough during the billion-year-plus cooling time of an average white dwarf to turn one sort of atmosphere into the other, whether the hydrogen is accreted or left over from the parent star.

Because the burning turns off for surface temperatures below 10,000K, one would expect continued accretion to build the hydrogen-rich population gradually back up again. This hypothesis cannot yet be properly tested, because (as Greenstein seems to have been the first to note in 1969) such faint, cool degenerate dwarfs are exceedingly rare. We do not yet fully understand the reasons for this, but diffusive hydrogen burning, which slows down the cooling process, may again be part of the picture. Or perhaps there were fewer suitable parent stars born 6-8 billion years ago than more recently.

A number of other topics, some of agreement, and some of at least friendly disagreement, surfaced at the October meeting. Several, like the evolutionary status of hot white dwarfs with both hydrogen and helium in their atmospheres, the nature of the faint, high-latitude blue stars, and the masses of degenerate dwarfs are subjects to which Greenstein, his students, and collaborators have made major contributions. Readers interested in pursuing them will find a more complete report of the symposium in the Quarterly Journal of the Royal Astrophysical Society later this year. □