Barium and CH Stars

The classical barium (or "Ba II") stars are red giants whose spectra show strong absorption lines of barium, strontium, and certain other heavy elements, as well as strong features due to carbon molecules. Together with the related class of CH stars, the Ba II stars were crucial in establishing the existence of neutron-capture reactions in stellar interiors that are responsible for the synthesis of heavy elements. More recently, the Ba II and CH stars have provided strong evidence for mass transfer in binary systems that drastically alters the surface composition of a companion star.

Barium Stars

Ba II stars were first recognized by W. P. Bidelman and P. C. Keenan in 1951. They are G-K giants whose spectra show an unusually strong absorption line of Ba II at 4554 Å, along with enhanced lines of Sr II and molecular bands of the CH, C_2, and CN molecules. The prototype is the 3rd-mag star ζ Capricorni. During the ensuing decade, studies of the spectra at high dispersion revealed that the abundances of numerous heavy elements are enhanced, notably the elements Sr, Y, and Zr; rare earths such as La, Ce, Nd, and Sm; and of course Ba. It was soon realized that these are exactly the elements expected to be synthesized when "seed" nuclei in the iron group are exposed to a flux of neutrons and are thus built up to higher atomic weights, on a timescale that is slow compared to the beta-decay timescale. This so-called "*s*-process" leads to high abundances of those chemical elements with low neutron-capture cross-sections (these being the "bottlenecks" in the neutron-capture chain), which are exactly the elements in the atomic-weight peaks around Sr and Ba.

CH Stars

The CH stars are a closely related class, actually first recognized even earlier than the Ba II stars by P. C. Keenan in 1942. They are essentially the Population II counterparts of barium stars, having similar enhancements of *s*-process elements and very strong bands of the CH molecule. However, CH stars have weak lines of the ordinary metals such as iron, since these stars belong to the old, metal-deficient population of our Galaxy.

CH stars are found both in the Galactic halo and in several globular clusters. The cluster ω Centauri contains the richest population of CH stars, about half a dozen.

The Luminosity Problem

By the early 1970's, the nucleosynthetic origin of the enhanced chemical elements in the Ba II and CH stars was reasonably well understood: they arise in stellar interiors when a flux of neutrons irradiates iron-group seed nuclei. This can happen, for example, during mixing associated with helium thermal pulses which brings together ^{13}C nuclei and alpha particles; each reaction releases a ^{16}O nucleus and a free neutron. Carbon is synthesized during helium burning in the cores of red giants. Subsequently, a mixing process causes the products of these reactions to be exposed at the stellar surface. In the mid-70's, however, detailed calculations of stellar evolution revealed a severe evolutionary problem: the sort of mixing required (called the "third dredge-up") only occurs in highly evolved, luminous asymptotic-giant-branch (AGB) stars. Yet the Ba II and CH stars were known to have only the luminosities of ordinary red giants, far too faint for any dredge-up to occur.

The problem was exacerbated by the discovery in 1974 by H. E. Bond of what he called "subgiant CH stars," which are F- and G-type stars of even lower luminosities, extending in some cases down to the main sequence, and showing similar patterns of enhanced heavy elements and carbon. Subsequent work has suggested that "dwarf barium stars" would be a better name for most of the members of this class, since most of them are not extremely iron-deficient. Even further down the main sequence, at spectral type K, a class of "dwarf carbon stars" was discovered in the late 1970's. All of these objects are far too faint to have synthesized *s*-process elements and carbon in their own interiors, let alone mixing them up to the stellar surface.

Moreover, none of these objects appear to be particularly rare stars; for example, large-scale spectroscopic surveys show that about 1% of red giants are members of the Ba II class, and a similar fraction of F-G dwarfs are barium dwarfs or subgiant CH stars.

The Solution

The solution to the luminosity problem came in the early 1980's, when R. D. McClure and his collaborators established that virtually all Ba II and CH stars are spectroscopic binaries, with fairly long periods and typical orbital separations of order 2 AU. This led to the realization that the binary system once contained an AGB star that mixed carbon and *s*-process elements to its surface, and then transferred this "polluted" material to a companion star. In many cases the companion would have been on or near the main sequence, and it is now seen as a dwarf barium star, dwarf carbon star, or subgiant CH star. When the contaminated main-sequence star evolves to become a red giant (or if the mass transfer is from the AGB star directly to a red-giant companion), it will be seen as a classical red-giant Ba II star (or as a CH star if the binary is a metal-poor member of Population II).

The Solution Confirmed

A direct test of the binary scenario would be to find a white-dwarf companion of a barium star. The above scenario in fact *demands* that all of the companions be white dwarfs, i.e., the remnants of the former AGB star.

In a stunning confirmation of the scenario, E. Böhm-Vitense showed in 1980 that ζ Cap has a hot white-dwarf companion, revealed in the ultraviolet by the *International Ultraviolet Explorer* satellite. Subsequent UV observations with *IUE*, and more recently by Böhm-Vitense and her collaborators with the *Hubble Space Telescope*, have revealed several more examples of Ba II stars with white-dwarf companions. In many cases, however, the white dwarf has faded to below detectability, and its presence shows up only in the variable radial velocity of the peculiar optical star.

The Pollution Mechanism

Recent work on the Ba II and related stars has focussed on the precise mechanism by which the AGB star contaminates its innocent companion. The two main possibilities are (a) that the AGB star evolves to fill its Roche lobe, and then spills substantial amounts of its envelope material onto the companion; and (b) that the AGB star pollutes the companion only through a stellar wind. In scenario (a), the outcome would usually be a common-envelope interaction, with a spiralling down of the orbit to a much smaller separation, so that the binary emerges as a cataclysmic variable rather than a barium star. However some authors have argued that stable Roche-lobe overflow is possible, thus avoiding the spiral-down. Scenario (b) is probably more likely at least for most barium stars, both because of their still large orbital separations, and because many of them have somewhat eccentric orbits, which would not be the case following Roche-lobe overflow.

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—Howard E. Bond, Space Telescope Science Institute, and Edward M. Sion, Villanova University