The Chemical Compositions of Five Stars Which Show Some of the Characteristics of Population-II*
Burbidge & Burbidge 1956 (BB1956) – A Classic

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At first glance, the paper’s title, ‘The chemical composition of five stars which show some characteristics of population-II’, is uncharacteristic and ordinary. Diving deeper into different sections of the paper reveals a well-thought experiment, critical analysis, and farsighted conclusions that remain most relevant to date. The authors probably found the five stars intriguing because they are peculiar among the solar neighborhood. They combined all aspects of available observations to understand the nature of these stars in the context of the Galaxy formation. They found a gradient in their chemical and kinematical properties and suggested this could be a result of the chemodynamical evolution of the Galaxy itself, which was a revelation in the 1950s.

Introduction to BB1956

The paper starts with a choice of five stars, HD 84123, HD 106223, λ Boötis, HD 161817, and 29 Cyg. It examines their properties with that of a typical population-II class\(^1\). The authors use the following to be possible characteristics of pop-II stars. Some of these properties were established at that time, and some were intuition from the authors.

- Stars with weak metallic lines compared to the solar neighborhood stars of similar temperatures. Weak metallic lines indicate the small number of heavy elements inside them that are processed by previous generations of stars and supernovae. So, these

\(^1\) Baade, in 1944, first noticed two populations of stars in a galaxy, luminous blue stars located along the spiral arms of a galaxy, called population-I, and faint red stars similar to globular clusters as population-II stars. George Gamow correctly explained these observations that pop-I are young and pop-II are old stars.

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Figure 1. HR-diagram is a plot of observable parameters of stars that gives an idea of mass–radius relation of stars which are not directly observable (except for a handful of stars). In the figure size of each circle represents the radius of stars. The colors of the circles indicate the amount of heavy elements (that is, heavier than hydrogen and helium) relative to the Sun. (Image Credit: SDSS collaboration)

stars might have formed during an early time in the Galaxy.

- Stars with high line-of-sight velocities passing through the galactic disk indicate they might have formed before the Milky Way disk formation.

- Stars occupying a position below the main-sequence of the solar neighborhood stars on the Hertzsprung–Russell diagram (shown in Figure 1) could be possible pop-II class because they are compact/hot, maybe due to higher hydrogen to helium ratio in their atmosphere. This characteristic of pop-II stars was proposed when such a chemical signature was not observed in stars, and the existence of parallel subdwarfs sequence below the main sequence was not known.

- Stars with low rotational velocities. Stars are expected to lose their angular momentum by interacting with stars/gas/dust clouds along their orbital path around the Galaxy. Hence older stars have smaller rotational velocities than younger stars that may have had fewer encounters of the disk.

At the time of this work, the nature and origin of stellar populations and their connection to galaxy formation and chemical evolution were not established. We know now that population-II stars are old stars formed when the Galaxy was only about 1–2 billion years old. The interstellar medium (ISM) had fewer heavy
elements than hydrogen (that was made during the Big Bang explosion) due to fewer supernovae that had time to enrich the ISM with heavy elements. Supernovae are one of the primary sources that make most of the heavier elements in the universe and what we see on the Earth. At later times, the heavy element abundance increased due to more supernovae and other stars polluting the ISM in the Galaxy. Most of the solar neighborhood stars, including the Sun, belong to the category of population-I stars, which are young and about a few billion years old. The age of the Galaxy is more than ten billion years.

1. The Process of Chemical Abundance Estimation of Stars

In order to estimate the chemical composition of these stars and assess their nature as young population-I or old population-II class, the authors obtain spectral absorption lines, similar to the dark absorption bands seen in Fraunhofer lines of the solar spectra. Light from the stars is collected through a telescope and passed on to a spectrograph that has a large grating to disperse the light into individual spectral lines.

It is finally recorded on a photographic plate by a camera. The strength of a spectral line depends on the number of atoms in the particular energy levels to contribute to emission or absorption, which also depends on the star’s temperature and the electron and gas pressure. More number of atoms would cause deeper spectral lines.

If the line depth increases linearly with the number of atoms, it is called the optically thin regime (as shown in Figure 2). As the number density increases, there are no more photons available at those particular wavelengths/energies to further increase in the line depth at the core of the line and is called the saturated line. Further increase in the number density of atoms would cause absorption in the wings of the lines, due to the contribution from the atoms in the Maxwellian tail of the velocity distribution. Thus in the wings, we see the Doppler-shifted photons corresponding to wavelengths far from the line core and contribute to absorption.
**Figure 2.** The line profiles indicate 3-regimes of optical depths, optically thin (a), saturated (b), and damping wings (c).

and make the lines broader.

**The curve of growth method** is a plot that relates the line strength and the number of absorbing atoms or molecules at different regimes of number densities as shown in (Figure 3). It can be divided into three regions—weak, saturated, and strong lines. Equivalent width/line strength varies linearly with the number of absorbing atoms for an optically thin medium and goes as the square root of the logarithm of number density in the saturated region and the square root of the number density in the collision dominated strong line wings.

Matching the observed points and theoretical curve of growth, one can estimate the number density of the atoms. A theoretical curve that is closer to the atmospheric parameter of a star is normally used. The small difference in the stellar parameters from the model and observations can be corrected by shifting the observed points horizontally and vertically. For example, all the atomic transitions due to neutral iron (FeI) should give the same iron abundance of the star. Hence assuming the atomic levels are populated as prescribed by Boltzmann’s equation, individual curves of growth of different transitions due to FeI lines can be shifted horizontally by an amount corresponding to the difference in temperature that will bring all the curves of FeI lines to merge,
giving the correct star’s temperature. Similarly, matching curves of two ionization states shifting vertically will give the electron density of the stellar atmosphere. By shifting the observed points to the theoretical curve of growth, the temperature and surface gravity can be estimated relative to the theoretical model curve and also the chemical abundances of the elements. The curve of growth analysis is used to estimate the stars’ chemical composition. This was a standard technique in the 1950s. The authors in this work used a relative curve of growth analysis of the five stars with respect to 95 Leo, an A-type star that shows sharp absorption lines and well estimated chemical abundances.

The analysis method takes care of possible systematics, including the calibration curve of the photographic plates corrected using a differential method. Effective temperatures were estimated using colors and estimating the horizontal shifts in the differential curve of growth for the best match of FeI lines. The electron densities were estimated using Stark broadening of Balmer line wings [1] and the number of visible Balmer lines, and applying Saha’s ionization equilibrium by matching the curve of growth of neutral and ionized lines, e.g., Fe/FeII, CrI/CrII, TiI/TiII.

Figure 3. The curve of growth shown in the figure correspond to the solar atmosphere by Aller (1964) [2]. In the optically thin regime (a), the number density is proportional to the equivalent width, while in the saturated regime, it is proportional to the square root of the logarithm of number density, and in the collision dominated region, the wings of the line contribute and is proportional to the square root of number density.

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Figure 4. Stark broadening of the hydrogen Balmer line \((n = 3 \rightarrow 2)\). For dwarf stars \((\log g = 5.0)\), the line wings are broad due to the Stark broadening of high electron density, compared to a giant star. The wiggle-like feature in the wings is due to weak absorption lines due to atomic lines.

2. Main Results of BB1956

They found that all five stars possess only one or two of the characteristics (out of 4 listed) to qualify as a population-II star. HD 106223, 29 Cyg, and \(\lambda\) Boötis were found to be metal-weak stars and extreme weakness in metallicity in the case of \(\lambda\) Boötis. However, their absolute magnitude, kinematics in the galaxy, and rotational speeds are not typical of pop-II stars. The authors note that “The occurrence of true main-sequence population-II stars (having population-II characteristics 2 and 3), but with the absolute magnitudes as high as +2.5 and temperatures of about 8000K, in the solar neighborhood would be expected to be much rarer than that of later type subdwarfs, if the globular-cluster, color-magnitude diagrams can be taken as a guide. In them, the bulk of the main sequence comes to an end at \(M = +3.5\)” and brilliantly conclude despite odds, the nature of the above three stars as pop-I stars. The three stars, including HD 84123, are now well-known pop-I \(\lambda\) Boo stars, a peculiar class of A-spectral type stars with a low abundance of heavy elements.

Finally, the target stars were arranged in terms of their population-II characteristics: HD 140283, HD 19445, \(\lambda\) Boötis, HD 106223, HD 161817,29 Cyg, HD 84123. Based on these observations, the authors suggest that “The occurrence of stars with intermediate chemical abundances (29 Cyg, HD 161817, and HD 106223) sug-
gests that element-synthesis processes have been going on con-
tinuously and that the relative numbers of stars which are partic-
ularly efficient in the synthesis processes are dependent on both
the stellar masses and the ages”.

As far as HD 161817 is concerned, its absolute magnitude is un-
known; it has a substantial space velocity (radial velocity = —363
km/sec; if the absolute magnitude were +2.5, the 2-component
would be —165 km/sec) and a small rotational velocity. “In
view of the high z-velocity of HD 161817, the possibility that it
is similar to stars on the horizontal branch3 of globular-cluster di-
agrams cannot be entirely ruled out.” Now it is well established
that HD161817 is pop-II horizontal branch star.

3 Horizontal branch stars are low mass core helium burn-
ing stars, and belong to the population-II category.

3. Results and Conclusion and Its Relevance to the Current
Context

This paper is interesting in two aspects in the current scenario in
astrophysics. This work seeds the first idea of galactic archaeol-
ogy4, the buzzword in the current Gaia era.

A quote from the paper, “Chemical elements are continuously
synthesized in every generation of stars and they contribute to en-
riching the galaxy at different times with different ratios of chem-
ic elements depending on their mass and age,” indicates an ini-
tial idea of galactic archaeology and galactic chemical evolution
decades ago. Even with the scanty sample of stars, the authors
could conclude that astrophysical sites of neutron-capture ele-
ments and the intermediate heavy elements such as alpha-capture
and Fe-peak elements are different. The ratio of neutron-capture
elements to iron will decrease at low metallicities. We currently
have evidence that neutron-capture elements are produced when
merging binary neutron stars explode in the post-merger phase.
Another farsighted intuitive statement in the paper is that large
galaxies like the Milky Way might have formed via mergers of
smaller proto-galaxies. A quote from the paper, “...in this very
early epoch is that material ejected after synthesis in other galax-
ies or proto-galaxies contaminated the material out of which the

4 Galactic archaeology is an area of research where as-
tronomers use the properties of stars to study the history of the
galaxy. How and when a galaxy is formed is imprinted in the
chemical makeup of the star, its location in the galaxy, and
how the star orbits around the galaxy. Astronomers can use
chemical composition to trace the age of a star and use com-
puter simulation to trace back the orbits of a large number
of stars around the galaxy and trace back its original position
several billion years ago. This allows us to reconstruct the ev-
olution of the galaxy.
extreme population-II stars condensed.”

The authors also suggest that “...there was an epoch earlier than that in which the extreme stars of population-II were formed, in which massive stars (perhaps 10–20 $M_\odot$) were formed”, seeding the idea of pop-III stars or the first stars. They also state that “We have no information as to whether or not stars with even greater under-abundance ratios are presently in existence”, indicating the possibility of more metal deficient stars in the galaxy. Currently, we know several hundreds of stars that are more metal-poor than in the 1950s (thanks to the extensive spectroscopic surveys such as SDSS & LAMOST). The record holder Fe-poor star is SMSS J0313–6708, with [Fe/H] = −7.3 (the relative ratio of Fe to hydrogen in the star is $10^{-7.3}$ of the solar value).

Despite its extreme weakness in metallic lines, the author suggested four of the five objects studied in this paper as possible population-I groups. These four objects are known as a class of $\lambda$ Boo-type stars, which belong to pop-I, A-type stars found from pre-main sequence to main sequence stage of evolution. In the current era, with accurate distances and proper motions from Gaia and radial velocities and chemical abundances from extensive spectroscopic surveys, accurate ages can be estimated, and a star can be tracked to its natal cloud using chemo dynamical modeling. The $\lambda$ Boo stars show extreme weakness in metallic lines and solar abundances of volatile elements such as C, N, O, and S. There is a correlation between the condensation temperature of the elements and the abundance [3], indicating dust formation and gas-dust winnowing. Accretion of refractory element poor gas by the star can reproduce the observed chemical abundance, which is interesting in the context of planet formation as the signatures of such process is retained in the host star abundances for a very long time. However, $\lambda$ Boo stars are also found to be pulsating, which gives a unique way to probe their interior structure and composition through asteroseismology, using Kepler, Transiting Exoplanet Survey Satellite (TESS), and other similar missions. The statement from the paper, “The rotational properties of population-II stars may assume great evolutionary
significance if the exceptions to correlations between classifications 2, 3, and 4 can be conclusively established.” As the authors rightly pointed out, estimating the ages of stars is still a hot topic of research. With the availability of Kepler data and large spectroscopic surveys, accurate gyrochronology may be a possibility for a large number of stars.

4. The Methodology in the Current Context

This paper used the differential curve of growth method instead of a currently widely used stellar model atmosphere methodology. A combined approach of a detailed atmospheric model-based analysis and the curve of growth method have more significant potential and are less explored. Mott et al. (2020) [4] combined a detailed 3D, non-local thermodynamic equilibrium (NLTE) radiative transfer models and applied curve of growth based correction to derive accurate lithium abundances for many stars. Even with the availability of large numbers of spectroscopic data and improved stellar atmospheric modeling and computing power, precision stellar abundances are still lacking. There are systematic differences due to wavelength coverage of the data, use of different atomic/molecular data, model atmospheres and treatment for radiative transfer, and even data processing. Many advocate a differential abundance analysis based on a set of well-estimated benchmark stars to derive precise abundances for addressing several astrophysical problems, including signatures of planet formation processes in the host stars’ chemical abundances (e.g., [5]). These can also be scaled to stars at more considerable distances, including external galaxies, to address the multitude of astrophysics problems within the local volume of galaxies. Now it is possible to estimate effective temperatures using direct methods, using distances from Gaia and stellar radius from interferometric observations. Also, asteroseismology provides vital insights into the stellar interior structure and abundances and allows a possibility to have well-characterized benchmark stars.

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Suggested Reading


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