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My research focuses on the intertwined goals of galactic archaeology and nuclear astrophysics: 1) deepening our understanding of the origin of the elements, which originated from the very first stars, 2) constraining the birth mass distribution (so-called initial mass function) of the first stars to scrutinize how they contribute to the Galactic chemical enrichment, and 3) unraveling the chemodynamical assembly history of the Galaxy. However, the first stars are thought to be massive, short-lived, and enriched the surrounding pristine gas shortly after their birth. Thus, I achieve these goals by indirect studies of their direct descendants, most metal-poor (metal-deficient) stars, by scrutinizing the unique and peculiar nucleosynthetic signatures imprinted on the atmospheres of these ancient, most metal-poor stars via spectroscopy and analyzing their kinematics.

**Current Projects (Galactic Archaeology/Nuclear Astrophysics)**

**Background**

When and how were the very first stars born? What were they like? What was their birth mass distribution? These are among the most long-sought questions in astronomy, because the formation of galaxies such as the Milky Way (MW), the Sun, the Solar System, the Earth, the Moon, indeed, all objects that incorporate metals (in astronomy, all elements heavier than H and He) had their origin in nucleosynthesis pathways that began with the very first stars in the Universe.

However, the very first stars have never been observed. It is thought that they were likely to have formed from gravitational instabilities in pristine (only H and He) gas 200~300 million years after the Big Bang. They were likely very massive (10-100 times the mass of the Sun) and thus short-lived. The first metals were synthesized during their stellar evolution and during supernovae explosions at the end of their lives. Through this process, the surrounding metal-free gas was polluted by the products of first-star nucleosynthesis. Multiple generations of star formation, evolution, and element production have since then enriched our galaxy to its present composition.

Astrophysicists did not recognize until the early 20th century that stars in our Galaxy have different chemical compositions from the Sun. The likely origin and evolution of metals were not known until the 1950s. Since then, large-scale surveys over the last four decades for the rare metal-deficient stars in the Milky Way (MW) halo have led to the discovery of many thousands of such stars. Among these, the sub-class known as CEMP-no stars are of particular interest. They are characterized by a distinctive abundance pattern, with carbon abundance that is strongly enhanced and heavy neutron-capture elements (such as Ba) that are under-abundant compared to Fe. Many of them, in particular, the extremely metal-poor (EMP; [Fe/H] < -3.0) CEMP-no stars (Beers & Christlieb 2005), also exhibit enhancements of light elements such as N, O, Na, and Mg. Also, the frequency of CEMP-no stars increases with decreasing metallicity; almost all of the ultra metal-poor (UMP; [Fe/H] < -4.0) stars are CEMP-no stars (Lee et al. 2013, Placco et al. 2014, Yoon et al. 2018a). CEMP-no stars are known to be predominantly members of the outer-halo population, characterized by retrograde, energetic orbits based on studies of their kinematics (e.g., Carollo et al. 2010, 2014, Lee et al. 2019). This outer-halo membership has suggested that CEMP-no stars had been accreted from low-mass dark matter-dominated mini-halos (their birthplaces) into the MW halo, while this notion has been challenged (e.g., Schönrich et al. 2011, 2014, Hansen et al. 2019). Thus, scrutinizing the EMP/UMP CEMP-no stars from both the MW halo and its satellite galaxies enables understanding of the nature of the first stars, Galactic chemical evolution (GCE), and the history of Galactic assembly.

**Decoding the nature of the first stars via the nucleosynthesis of the most metal-poor stars**

Obtaining a better characterization of the first-star nucleosynthesis is critical for understanding the nature of the first stars, which requires detailed chemical abundance analyses of various elements in order to determine the likely astrophysical progenitors (parent stars) among various suggested possibilities, including "faint supernovae" and "spinstars (rapidly rotating massive stars)." The relative abundances of C, N, and O are among the most important factors to differentiate between these models, which is linked to my doctoral research about rapid rotational effect on chemical composition. Recently, I recognized that the CEMP-no stars can be sub-divided into at least two groups (Group II CEMP-no and Group III CEMP-no), based on their distinct morphology in the A(C)-[Fe/H] space, indicating the likely existence of multiple pathways for their formation. I also found that this distinct CEMP-no group morphology is identified in the absolute abundance spaces of A(Na)-A(C), A(Mg)-A(C), and A(Ba)-A(C) as well (Yoon et al. 2016, 2019). Thus a full detailed abundance analysis is crucial for the characterizing the nucleosynthesis happened during the evolution of the first stars.

However, several of the light elements (in particular, N and O) are not readily measurable, even for the known CEMP-no stars, with high-resolution spectroscopy alone. I plan to obtain C, N, O abundances from molecular bands via midium-resolution spectrographs, the [LBT/MODS](https://sites.google.com/a/lbto.org/mods/)and [LUCI (near-IR)](https://sites.google.com/a/lbto.org/luci/). By combining these abundances with existing elemental abundances from high-resolution spectroscopy, I will conduct a full abundance analyses for the known CEMP-no stars, and better characterize the possible astrophysical nucleosynthesis pathways responsible for their origin.

**Hunting for the most metal-poor stars and developing analysis tools**

The slow discovery rate of UMP stars (~25 stars in 25 years as of 2016) has hampered progress in understanding the nature of the first stars. The conventional sub-classification scheme for CEMP-no stars requires a measured Ba abundance, which can only be made with high-resolution spectroscopy -- a time-intensive effort usually carried out with large telescopes. Thus, my colleagues and I have recently devised a method to identify CEMP-no stars with a success rate similar to the conventional Ba method that only requires an absolute carbon abundance measurement (A(C)) that is readily obtained with medium-resolution spectroscopy on smaller telescopes (Yoon et al. 2016). I have applied this method to the medium-resolution spectroscopic data from the AEGIS survey in the Southern Hemisphere and identified ~700 CEMP-no stars, confirming that they are predominantly members of the outer-halo population (Yoon et al. 2018). This method has also been applied to various samples such as spectroscopic data from SDSS, creating the first map of the distribution of [C/Fe] in the MW halo (Lee et al. 2017), and a medium-resolution spectroscopic study of the MW dwarf spheroidal galaxy (dSph) Sculptor (Chiti et al. 2018).

Using the fact that the increasing fraction of CEMP stars with decreasing metallicity and my discovering method for UMP stars, I have been actively observing and analyzing the very cool (<4500K) CEMP stars using the [Large Binocular Telescope(LBT)/MODS (optical)](https://sites.google.com/a/lbto.org/mods/) and the [Gemini Telescopes/GMOS](https://www.gemini.edu/sciops/instruments/gmos/). The preliminary work has been published in Yoon et al. 2018b. I have also led a group of graduate students for a project of developing a stellar parameter pipeline specific to these types of stars.

**Formation (assembly) and chemical evolution history of the Galactic halo**

All of the chemical elements play potentially important roles in our understanding of GCE, since the production history of each element can follow different nucleosynthesis pathways such as different astrophysical processes, sites, timescales, and/or masses of the stars for chemical enrichemnt. In particular, I have studied the cosmic evolution of iron and carbon in the MW and implications of their spatial distribution on the formation and evolution history of the MW halo (Yoon et al. 2018a).

The recent study using high-resolution data with Gaia DR2 kinematics by C. Hansen et al. 2019 does support that CEMP-no predominantly come from the outer halo, while another kinematical study of Lee et al. 2019 using a large SDSS data set with Gaia DR2 supports the predominant outer halo membership of CEMP-no stars.

Further, I have found strong evidence that the halo CEMP-no stars were indeed accreted from their likely birthplaces (disrupted first galaxies), by showing that the similar CEMP-no groups exist among the stars in satellite dwarf galaxies (Yoon et al. 2019).

**Previous Projects (Rapid Rotation/Stellar Evolution)**

**Summary**

Unlike late-type (cool and low-mass) stars such as Sun, early-type stars such as Vega (Teff > 10,000K and Mass > 2 solar masses) rotate rapidly, faster than 50% breakup of a star. However, the role of rotation has been greatly underestimated, and thus, there have been numerous discrepancies between the models and the observations. Since rotation obscures the interpretation of the observed data, my main work was to numerically simulate rapidly rotating stars (so-called gravity-darkened Roche models, von Zeipel 1924) and predict both interferometric and spectroscopic observables for comparison with the observed data. Then I decoupled rotational effects from the physical properties such as temperature, radius, composition, mass, and in turn age by measuring accurate and precise true rotational velocity by using both high angular resolution interferometry and high-resolution spectroscopy.

**Rotational effect on stellar surface of early-type stars**

***High angular resolution long-baseline interferometry***

A rotating star can be modeled by a gravity-darkened Roche spheroid (von Zeipel 1924), allowing us to predict measurable interferometric quantities (visibility amplitude and closure phase) that are related to oblateness, temperature gradients, and surface brightness asymmetries. By adding observational data such as parallax, B-V color, projected rotational velocity, and V magnitude to the modeling, I computed not only all the required physical parameters but also the probabilities of detection of oblateness and asymmetry of early-type stars and to produce lists of potential targets for such instruments as the Navy Precision Optical Interferometer (NPOI) and the Very Large Telescope Interferometer (VLTI). But rotation can also introduce uncertainty when one estimates the visibilities of early-type stars that are used as standard stars for calibration of all sorts of astronomical observations. Therefore, I estimated the effects of rotation on potential calibrators by constructing probability distributions of the predicted visibility for the individual objects. This lets astronomers judge the adequacy of their interferometry calibrators. I calculated for a number of configurations of existing long-baseline interferometers such as CHARA, NPOI, SUSI, and VLTI. The detailed description can be found in Yoon et al. (2006, 2007).

**Effect of rotation on line profiles, chemical composition, age and mass of stars**

***High-resolution spectroscopy***

With the detections of the interferometric signature of rapid rotation in Vega ( ~ 93% break-up velocity of the star and yet almost pole-on, Peterson et al. 2006a, Aufdenberg et al. 2006), as well as studies of peculiar line shapes in its spectrum (Hill, Gulliver, & Adelman 2004), a number of questions were raised about this fundamental standard, such as its composition, mass, and age. A full synthesis of the spectrum using gravity-darkened Roche models was necessary to reproduce the peculiar line profiles, and this called into question whether a composition analysis based on standard plane-parallel model atmospheres is adequate.

To resolve some of these questions, I have modeled Vega as a Roche spheroid seen nearly pole-on with a temperature gradient across the surface, using ATLAS9 model atmospheres locally. Integrating over the disk, I computed the synthetic spectra for comparison with the observations. These models appear to reproduce the peculiar line profiles very nicely and give confidence to the abundances I obtain for Vega. For observational data, I have utilized spectra from the ELODIE database and co-added 49 spectra, resulting in improving the SNR from about 250 for a typical spectrum to about 1,800 for the combination, necessary to fit Vega's unusual peculiar weak lines.

In order to get a good fit to the shapes of the weak lines, I found that I needed to convolve the spectrum with a Gaussian that is substantially broader than the nominal resolution of the ELODIE spectra (R~ 42,000), amounting to what would be interpreted as adding 10 km/s of macro-turbulence (which can be considered as weather pattern in Vega's atmosphere). I also found that the peculiar appearance of the lines depends on how the excitation potentials amplify the temperature gradient, which is substantially large in rapid rotators (for Vega, the temperature difference between the pole and the equator is about 2,500K.). From the abundance analysis, I found that Vega shows the peculiar abundance pattern of a λ Bootis star, which is a class of metal-poor Population I A-type stars with normal rotation, as previously suggested (e.g., Venn & Lambert 1990). I studied the effects of rotation on the deduced abundances and showed that the dominant ionization states are only slightly affected compared to analyses using non-rotating models. I argued that the rapid rotation requires the star to be well mixed and in turn, the deduced composition is a bulk property not limited to the surface. The deduced composition (Z~0.009) led to mass (M~2.1 solar masses) and particularly age (540 million years) that are quite different compared to what is usually assumed (M~2.3 solar masses and age~360 million years). The increased age I obtained would make Vega an unlikely member of the Castor moving group. The details of this analysis were reported in Yoon et al. (2008).

**Measurement of accurate stellar parameters of Vega and updating Vega's evolutionary status**

***Simultaneous analysis of interferometry and spectroscopy***

As my final doctoral analysis, I had done a simultaneous fit of interferometric data (triple-phase of the NPOI) with spectrophotometric data (spectral energy distribution), metal line profiles of Ca I λ6162 and Mg I λ4702 from the ELODIE archive having the peculiar line shapes, and hydrogen wings of three Balmer lines which provides the maximum number of possible constraints on the models and thus gives a more reliable determination of physical characteristics, especially mass. Based on this simultaneous fitting of a Roche model to the data, I discovered not only that Vega's rotation rate is somewhat slower (angular rotation rate of ω~0.88) than the previously determined (ω~0.93, Peterson et al. 2006b, Aufdenburg et al. 2006) but also that the derived mass directly from Balmer lines is less massive (M~2.14 solar masses) than the currently assumed value. By locating its derived mass, radius, and luminosity here on an evolutionary track, I obtained its metallicity of Z~0.008 consistent with the value derived from surface composition and in particular is significantly less than solar. In turn, the lower mass suggests that it is nearly 470 million years and older than previously assumed (360 million years). The low bulk metallicity strongly argues that Vega was formed with a metal-poor composition. The agreement between the bulk and the surface compositions argues that it remains well mixed, consistent with its rapid rotation. But most importantly, the low bulk metallicity creates a significant challenge to identify a process that could produce a relatively young star this depleted in heavy elements. I also note that if Vega is representative, this question could extend to the formation of λ Boo stars generally where the abundance anomalies have until now been assumed to be confined to the surface layers. This analysis was reported in Yoon et al. (2010).