Postprint: Study of Sequoia Substructure Based on LAMOST Data

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Abstract

Sequoia is a retrograde substructure originating from a merger event between a dwarf galaxy and the Milky Way. We first introduce the discovery of Sequoia and comprehensively analyze constraints on this substructure in phase space and its chemical properties from various literature sources. Subsequently, using LAMOST DR8 spectroscopic data combined with Gaia EDR3 astrometric data, we construct a sample containing spatial positions, velocities, and metallicities. With this sample, we first analyze the Sequoia substructure according to source selection criteria from the literature, then independently isolate this substructure using the DBSACN clustering algorithm and conduct a detailed analysis, and subsequently compare its chemical properties with those of Gaia-Enceladus-Sausage (GES). Overall, the Sequoia substructure exhibits more metal-poor metallicities and lower α, Al, and Ni abundances compared to the GES structure; however, for other elemental abundances obtained from low-resolution spectra, obvious differences between these two substructures are difficult to discern. Accurately determining the chemical abundance pattern of this substructure requires larger-scale follow-up high-resolution spectroscopic observations.

Full Text

Preamble

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Study of the Sequoia Substructure Based on LAMOST Data

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Abstract

Sequoia is a retrograde substructure originating from the merger of a dwarf galaxy with the Milky Way. This paper first introduces the discovery of Sequoia and comprehensively analyzes the constraints on this substructure in phase space and its chemical properties as reported in the literature. Subsequently, using LAMOST DR8 spectroscopic data combined with Gaia EDR3 astrometric data, we construct a sample containing spatial positions, velocities, and metallicities. With this sample, we first analyze the Sequoia substructure according to the source selection criteria from the literature, then independently isolate this substructure using the HDBSCAN clustering algorithm for detailed analysis, and finally compare its chemical properties with those of Gaia-Enceladus-Sausage (GES). Overall, the Sequoia substructure exhibits more metal-poor abundances, lower α-element, Al, and Ni abundances compared to GES. However, abundances of other elements derived from low-resolution spectra show no clear distinction between these two substructures. Accurately determining the detailed chemical abundance pattern of this substructure requires larger-scale high-resolution spectroscopic follow-up observations.

Keywords: Sequoia; Galactic halo; substructure; abundances

1. Introduction

According to the cold dark matter model, hierarchical merging during the formation of the Milky Way produces rich phase-space structures. These structures evolve from early spatially clustered stellar streams into kinematic and chemical substructures. Studying these substructures from kinematic, chemical, and dynamical evolution perspectives is crucial for understanding the formation of the Milky Way. Numerous merger events have been discovered, among which GES is the remnant of the most significant merger event that formed the Galactic halo, with a progenitor stellar mass of approximately $(10^{8 \cdot 85}\text{-}10^{9 \cdot 85})$ M .

In addition to GES, another accretion event—the Sequoia substructure—has also been identified. In 2019, Myeong et al. discovered that several metal-poor, retrograde globular clusters in the Galactic halo likely originated from a dwarf galaxy accreted by the Milky Way, and they coined the term "Sequoia" to describe this accretion event. They estimated the stellar mass of Sequoia' s progenitor to be approximately 5×10^7 M , with a total mass of about 10^{10} M . Although significantly smaller than GES, Sequoia possesses unique chemodynamical characteristics: its member stars are on retrograde orbits with typical eccentricities around 0.6, whereas GES velocities are near zero and primarily on radial orbits. On average, Sequoia members have more metal-poor [Fe/H] than GES, lower by about 0.3 dex. At the same [Fe/H], Sequoia shows higher elemental abundances; for example, at [Fe/H] = -1.5, Sequoia' s [Al/Fe] is higher than that of GES. They speculated that Sequoia and GES might have been accreted during the same period and are mutually related.

Since then, research on Sequoia has gradually developed, yet its properties remain controversial. This substructure primarily provides high-energy, retrograde rotating stars in the Galactic halo, but the nature of its accretion event is not well understood. Using available survey data including LAMOST, Gaia, APOGEE, and RAVE to identify member stars of the Sequoia substructure, investigate its relationship with other known small retrograde substructures, and conduct chemical and kinematic analyses of its members is of great significance for deepening our understanding of the progenitor galaxy' s properties and the overall merger history.

This paper is organized as follows: Chapter 2 reviews the development and current status of Sequoia substructure research; Chapter 3, building on previous studies and referencing their member selection criteria, combines LAMOST DR8 data to compare chemical abundance ratios between Sequoia and GES, and discusses how different member selection criteria may affect the results; Chapter 4 further explores the use of the HDBSCAN clustering algorithm for clump selection and conducts chemical abundance analysis; Chapter 5 presents our summary and outlook.

2. Research Status

Recent research on the Sequoia substructure has focused on kinematic and chemical properties, with different criteria emerging for selecting member stars. Koppelman et al. and Matsuno et al. selected members based on angular momentum (Lz) and orbital energy (E), while Myeong et al. and Feuillet et al. used action variables (J).

Using Gaia astrometric data, Myeong et al. noted that Sequoia and GES show clear differences in action space distribution: Sequoia is retrograde with J /Jtot $<$ -0.5 (where J is the azimuthal action and Jtot is the sum of absolute values of azimuthal, vertical, and radial actions), whereas GES has |J /Jtot| $<$ 0.07. Using APOGEE DR14 data, they further pointed out that GES and Sequoia have different [Fe/H] distributions, with GES peaking at [Fe/H] = -1.3 and Sequoia peaking at [Fe/H] = -1.6. They also found that both substructures have [Mg/Fe] and [Al/Fe] lower than the Milky Way and distinct from each other.

To further understand Sequoia' s properties, Koppelman et al. constructed a sample of 8,738,322 stars with six-dimensional phase-space information and high parallax precision (parallax over error > 5). The sample stars came from Gaia GVS, APOGEE, LAMOST, and RAVE, among which 3,404,432 stars have [Fe/H] information and 189,444 have chemical abundance information. Using the HDBSCAN clustering algorithm, they identified several distinct substructures and found that Sequoia’ s orbital energy range is smaller than previously estimated and confined to high energies. Sequoia’ s progenitor may have been a low-mass galaxy, but its properties cannot be fully determined due to overlap with GES debris in both integral-of-motion space and chemical abundance space. They noted that the retrograde halo can be divided into two components (separated by their orbital energy values in E-Lz space), with the high-energy component corresponding to Sequoia and the low-energy group possibly related to another accretion event called Thamnos. [Figure 1: see original paper] shows the distribution of member stars in En-Lz space from Koppelman’ s work, where En is the total energy (corresponding to energy E in this paper). The contours indicate the range of simulated dwarf galaxies placed on the remnants of Sequoia and Thamnos 1 and 2, with inner contours at $M^* = 5 \times 10^6$ M and outer contours at $M^* = 10^8$ M .

In 2020, Naidu et al. used H3 spectroscopic survey data combined with Gaia astrometric data to construct a sample of 5,684 giant stars with Galactic latitudes above 40° ($|z| > 2$ kpc), identifying the high-α disk, local halo, Sagittarius, GES, Helmi streams, Sequoia, and Thamnos substructures. They found that Sequoia overlaps with two other retrograde substructures characterized by different [Fe/H], which they named Arjuna and I’ itoi, studying the three substructures together. Based on elemental abundance data from the H3 survey, they found that Sequoia has a mean [Fe/H] of -1.6 dex, while Arjuna (containing most high-energy retrograde members) peaks near -1.2 dex, and I’ itoi peaks below -2.0 dex. They classified $[Fe/H] < -2$ as I’ itoi, $-2 < [Fe/H] < -1.6$ as Sequoia, and $-1.6 < [Fe/H] < -1.2$ as Arjuna. However, this division’ s limitation is that it cannot discuss differences in metallicity between Sequoia and GES based on such selection criteria.

Feuillet et al. used Gaia DR2 and APOGEE DR16 data to test different Sequoia member selection conditions. Under the condition $-1.0 < (Jz - JR)/Jtot < 0.1$, they selected Sequoia samples using $-1.0 < J /Jtot < -0.4$ as the standard, and Sequoia06 samples using $-1.0 < J /Jtot < -0.6$ as the standard. They pointed out that GES and Sequoia samples have similar Mg and Al abundances when $[Fe/H] < -1.3$. When $[Fe/H] > -1.3$, the Sequoia sample shows large scatter, indicating that abundance patterns correlate with kinematic criteria used for member selection. The larger Sequoia sample diverges in [Mg/Fe] and [Al/Fe], while the Sequoia06 sample mainly contains high-[Mg/Fe] and high-[Al/Fe] stars. They concluded that the most likely mean metallicity representing Sequoia members is between -1.5 and -1.3 dex, depending on contamination removal criteria, and stars with $[Fe/H] > -1.0$ are unlikely to be Sequoia members. They also noted that the small number of Sequoia member candidates makes robust characterization difficult, and a significant fraction of stars selected in action space are not members, suggesting that selection criteria in this space should be applied with caution.

To finely investigate Sequoia’ s chemical properties, Matsuno et al. performed differential abundance analysis on high signal-to-noise, high-resolution spectra, noting chemical differences between Sequoia and GES members. Within the metallicity range -1.8 < [Fe/H] < -1.4, eight Sequoia members show lower [Na/Fe], [Mg/Fe], [Ca/Fe], [Ti/Fe], [Zn/Fe], and [Y/Fe] than expected for GES. The abundance differences for [Na/Fe] and [Mg/Fe] are about 0.2 dex, while other abundance ratios differ by about 0.1 dex. They argued that since the Sequoia substructure is smaller than GES and has lower mean metallicity, its progenitor galaxy was likely a disrupted dwarf galaxy smaller than GES’ s progenitor.

For a comprehensive study of Sequoia’ s chemical abundances, Horta et al. selected Sequoia members based on previous criteria in angular momentum-energy space (Lz-E) and action space (J) using APOGEE and Gaia data, and compared abundances with GES members. Quantitative comparison indicated that Sequoia and GES have similar chemical properties, confirming Koppelman et al.’ s hypothesis that low-eccentricity, retrograde, relatively high-energy stars identified as Sequoia might have originated from the GES merger. Repeating Matsuno et al.’ s procedure with APOGEE data, they found Sequoia and GES to be very similar in APOGEE’ s sampled chemical space. They noted that although further data and modeling are needed, Sequoia and GES may share a common origin based on chemical composition data.

3. Analysis Based on LAMOST Data

To verify how different selection criteria affect results, we cross-matched LAMOST LRS DR8 with Gaia EDR3 to establish a sample of 554,107 stars. Using radial velocities from LAMOST DR8, positions and proper motions from Gaia EDR3, and distances calculated by Anders et al. based on Gaia EDR3, we computed stellar positions (x, y, z) and velocities (vx, vy, vz) in a right-handed Galactocentric coordinate system. We then calculated orbital parameters for the sample stars using Galpot and the Galactic gravitational potential, including energy E, angular momentum in the z-direction Lz, pericenter Rpr, apocenter Rap, maximum distance in the z-direction Zmax, guiding radius Rg, and eccentricity e. We adopted a Sun-Galactic Center distance of 8.21 kpc, a solar position 14 pc above the Galactic midplane, solar motion relative to the Local Standard of Rest (LSR) of (11.1, 12.24, 7.25) km s^{-1}, and an LSR rotation speed around the Galactic Center of 233.1 km s^{-1}. We selected candidate Sequoia members according to the criteria given by Koppelman et al. and Naidu et al., and compared chemical abundances between Sequoia and GES using [Fe/H] and [X/Fe] information provided by LAMOST.

To determine which criterion better reveals differences between Sequoia and GES, we employed two different Sequoia member selection criteria. First, following Koppelman et al.’ s criteria: $0.4 <$ < 0.65 (where is circularity calculated using Wetzel’ s formula, $= 1 - e^2$, with e being eccentricity), $1.35 <$ E $< -1.0 \times 10^5$ km^2 s^{-2}, and Lz < 0, we selected Sequoia members shown as red scatter points (see [Figure 2: see original paper]). As mentioned earlier, Naidu et al. proposed that Sequoia overlaps with two other retrograde substructures characterized by different [Fe/H], which they named Arjuna and I’ itoi, studying the three substructures together. Therefore, based on kinematic selection criteria, we further separated Sequoia from the three substructures according to their [Fe/H] values. Using > 0.15, E $> -1.6 \times 10^5$ km^2 s^{-2}, Lz $< -0.7 \times 10^3$ kpc km s^{-1}, and $-2 <$ [Fe/H] < -1.6, we selected Sequoia members shown as green scatter points. GES members were selected according to Horta et al.’ s criteria $|$Lz$| < 0.5 \times 10^3$ kpc km s^{-1} and $-1.6 <$ E $< -1.1 \times 10^5$ km^2 s^{-2}, shown as dark blue scatter points (selected only by Lz and E, with no secondary processing at the intersection of red and blue samples).

After selecting members, we compared chemical abundances between Sequoia and GES using elemental abundance information from LAMOST DR8. We examined the distributions of [Mg/Fe], [Al/Fe], [Ni/Fe], [C/Fe], [N/Fe], and [Mg/Mn]. As shown in [Figure 3: see original paper], the [Fe/H] distribution of Sequoia under Koppelman’ s selection criteria is slightly narrower than that of GES, while Naidu’ s criteria first divide [Fe/H], fixing the Sequoia [Fe/H] distribution within $-2 <$ [Fe/H] < -1.6, which is significantly narrower than Koppelman’ s distribution and lacks comparative value.

The Koppelman-selected Sequoia shows overall lower metallicity than GES, but its density distribution substantially overlaps with GES’s central region, showing no significant difference and preventing clear distinction between Sequoia and GES based on abundances. The Naidu-selected Sequoia has essentially the same metallicity distribution as GES in the overlapping [Fe/H] range, and since Naidu’ s criteria pre-divide metallicity, they lack comparative value.

4. Clustering Selection

For deeper investigation, we used the HDBSCAN clustering algorithm to attempt detection of a purer Sequoia structure. HDBSCAN (Hierarchical Density-Based Spatial Clustering of Applications with Noise) is unaffected by density distributions and can find clusters of varying densities. We set min_{samples} = 3, min_{{{cluster}}{{size}}} = 18, and cluster{{{selection}}_{{method}}} = “leaf” , with other parameters at default values. We used E, Lz, ecc, and [Fe/H] as algorithm inputs—parameters commonly used for finding substructures in the stellar halo. We selected all stars within 5 kpc of the Sun and applied the condition $|$V $-230| < 180$ km s^{-1} to reduce disk star contamination.

[Figure 4: see original paper]a shows the clusters found by HDBSCAN, with different colors representing different clusters. In the retrograde, high-energy region, a dark red cluster clearly separates from others, corresponding to the Sequoia structure, which we mark with dark red crosses for distinction. Due to differences in data, gravitational potential parameters, and samples, the distribution regions and numbers of Sequoia and GES in [Figure 4: see original paper] differ from those in [Figure 1: see original paper]. We mark all clusters whose members satisfy $|Lz| < 0.5 \times 10^3$ kpc km s^{-1} and $-1.8 < E < -1.3 \times 10^5$ km^2 s^{-2} in dark blue, corresponding to the GES structure (see [Figure 4: see original paper]b).

Based on the selection results, we compared and analyzed the chemical abundances of these two groups of clusters. As shown in [Figure 5: see original paper], the left cluster' s members have [Fe/H] distributed mainly in the range -2.0 to -1.0, clearly more metal-poor than the overall sample, with [Mg/Fe], [Al/Fe], and [Ni/Fe] significantly lower than the central cluster. The density contour plots reveal that this result shows clearer distribution differences than previous standard comparisons, but the two structures still overlap and are not clearly separated.

5. Summary and Outlook

Retrograde rotating stars are generally considered to have formed through accretion. Since Myeong et al. named Sequoia, research on this substructure has continued. Using different data samples and different methods in different phase spaces, the Sequoia substructure can be detected. It has distinct kinematic features—retrograde and high-energy. Some studies suggest that Sequoia and GES not only show clear differences in kinematic space but also exhibit distinct chemical abundance patterns, while others find Sequoia difficult to distinguish from GES in chemical space.

Using LAMOST data, we constructed a highly consistent sample. First, we selected Sequoia members according to literature criteria and analyzed their chemical properties using LAMOST' s value-added chemical abundance catalog. Finally, to obtain purer Sequoia members, we applied the HDBSCAN method to our sample, testing parameters continuously to identify reliable Sequoia members and analyze their chemical properties. Overall, Sequoia is more metal-poor than GES, with α-element, Al, and Ni abundances showing consistently lower trends, but determining this substructure' s detailed elemental abundance pattern requires high-resolution spectroscopy. Our work also provides observational targets for future high-resolution spectroscopic follow-up.

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