Stellar Populations as Building Blocks of Galaxies
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Decomposition of the Galactic Disk: Abundances and Kinematics

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Abstract. To this contribution we present a brief review of our recent abundance surveys (Reddy *et al.* 2003; Reddy *et al.* 2006) of the Milky Way galaxy. Survey focussed on controlled samples of stars selected based on their kinematic properties to belong either thin disk, thick disk or halo components of the Galaxy. Abundance and kinematic results were obtained for about 400 F-, G- and K- dwarfs. Abundances for 22 elements representing different production mechanisms (α-process, p-capture, Fe-peak, s- and r-process) and sites (AGB, SNIa, SNII) were obtained using high quality and high resolution echelle spectra.

Results showed thin and thick disk components are distinct stellar populations with different chemical history. The ratios of α-elements and a few other elements (like Al, V, and Co) are clearly enhanced for stars in the thick disk compared to thin disk stars at given metallicity. Abundance ratios for halo and thick disk stars are very similar. Dispersion in [X/Fe] ratios at given metallicity is comparable to measurement errors inferring lack of cosmic' scatter. Thick disk stars are older (10-13 Gyrs) compared to their counter parts (1-10 Gyrs) in the thin disk. Abundance results for thin and thick disk stars favor the models of hierarchical formation of the galaxy.

Keywords. Milky Way, Abundances, Kinematics, Galactic disk, Halo, Thick disk, Thin disk

1. Introduction

Making use of kinematics and abundances of individual stars to understand formation history of our galaxy traces back to the seminal paper by Eggen, Lyndon-Bell and Sandage (1962). They showed stars with little or no UV excess move in nearly circular orbits whereas stars with high UV excess (or more metal poor stars) move in highly eccentric orbits. The so called rapid collapse model for the formation of our galaxy emerged. The data also showed two components halo and the disk which are distinct in kinematics and metallicity. Gilmore & Reid (1983) were the first to suggest that the Milky Way disk is composite of two different populations. The star count analysis indicated two components with scale height of 300 pc for the dominant thin disk and much larger scale height of 1350 pc for the second component known as thick disk.The other significant paper in the context of Galactic disk abundances and kinematics is by Edvardsson *et al.* (1993). Their study of abundances of 13 elements for about 200 stars defined the chemical evolution of the Galactic disk. They pointed out the anomalous high abundance ratios [X/Fe] of α-elements for stars of less mean radii (R) (mean of apo- and peri galactic distances) compared to stars of larger R at given metallicities. However, at no occasion they attributed this anomaly to the different stellar populations within the disk. Instead they suggested the anomaly to the efficient star formation closer to the Galactic center. In fact, this was one of the motivating factors for us to initiate stellar abundance survey of the Galactic disk (Reddy *et al.* 2003; Reddy *et al.* 2006).

Gratton *et al.* (1996) showed the abundance ratios of α-elements [O/Fe] and [Mg/Fe] are different for thick and thin disk but the ratios are similar for thick and halo stars. Later

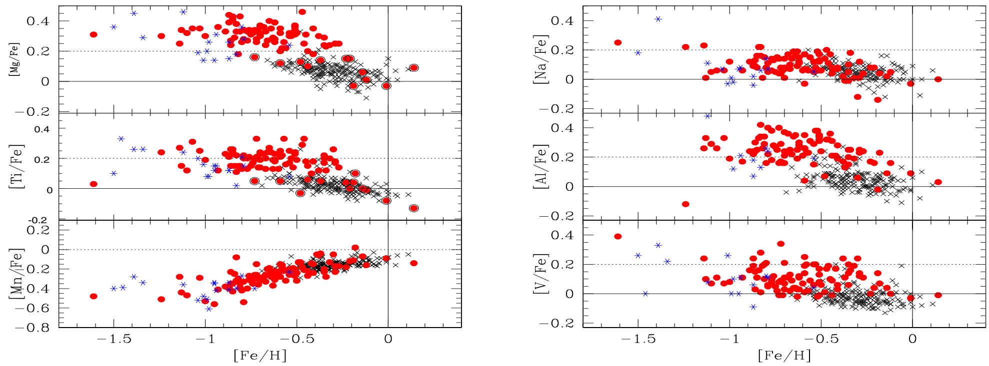

Figure 1. *Left panel*: Sample abundance ratios for thin (crosses) and thick disk (filled circles) stars. Note the higher values of [Mg/Fe] and [Ti/Fe] for stars in the thick disk compared to thin disk stars at given [Fe/H]. Abundance ratio [Mn/Fe] is same for both the components. *Right panel*: Note the higher [Al/Fe] and [V/Fe] ratios for stars in the thick disk and similar values of [Na/Fe] for both thick and thin disk stars.

Fuhrman (1998) showed clear enhancement of [Mg/Fe] for thick disk stars suggesting thick disk composition is dominated by SNII. The results were confirmed by Prochaska *et al.* (2000) who derived abundance ratios of 21 elements but for a small sample of 10 thick disk stars. Though the evidence for the existence of chemically distinct thick disk emerged, the nature of the thick disk was elusive due to either a small sample of stars or a few elements. What is the metallicity range of thick disk? Does thick disk shows slope in the correlations of [X/Fe] and [Fe/H] similar to thin disk? Does thick disk's chemical evolution is similar to thin disk? These are some of the questions which could be answered by systematic study of large number of stars. This prompted many new investigations of elemental abundances in thin and thick disk stars, notably, Feltzing, Bensby & Lundström (2003), Reddy *et al.* (2003), Bensby *et al.* (2005), and Reddy *et al.* (2006). Here, I present a brief summary of the results from these surveys particularly, Reddy *et al.* (2003, 2006) as they analyzed larger number of stars for both the thin and thick disk components.

2. Results and Discussion

2.1. *Composition of the Thick Disk*

Results for some of the key elements are shown in Figure 1. Ratios of [Mg/Fe] and [Ti/Fe] are higher for thick disk stars compared to thin disk stars at given [Fe/H] suggesting distinct chemical history for thin and thick disk populations. The α-elements Mg and Ti are known to be produced in SNII and their higher values suggest the dominant contribution from SNII products. Near horizontal relation of [Mg/Fe] and [Ti/Fe] with [Fe/H] may suggest the lack of SNIa products and fast formation of thick disk in about 2-3 Gyrs. Apart from α-elements there are few other elements like Al, Sc, V, Co, and possibly Zn which show enhanced abundance ratios in thick disk stars relative to thin disk. These elements are thought to be produced in equal proportion both in SNIa and SNII although the exact mechanism and the production sites are not known. For example Na and Al are predicted to be produced either in SNIa or SNII in very similar proportion (e.g; Kobayashi *et al.* 2006). Results in Figure 1 show contrary. Higher ratio of [Al/Fe] for stars in thick disk is a clear indication of Al's dominant production in SNII. The puzzling abundance ratios are also reported by Prochaska *et al.* (2000) and Bensby *et al.*

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(2005). One may not attribute this to the artifact or to the non-LTE effects as difference is seen for stars of almost similar atmospheric parameters (T_{eff}, log g, [Fe/H]).

2.2. *Chemical Evolution of the Thick Disk*

Is thick disk a frozen entity with no current star formation or is it evolving? Chemical history of the thick disk can be deduced by plotting abundance ratios of elements with different nucleosynthesis history. Here, we consider Mg-like elements (α-process) against Fe. The run of [Mg/Fe] and [Ti/Fe] against [Fe/H] in Figure 1 may suggest two representations for the thick disk evolution. First one is by Feltzing *et al.* (2003) who proposed the constant evolution of [Mg/Fe] upto [Fe/H] ≈ -0.3 and the rapid drop in [Mg/Fe] at about -0.3 (the so called "knee") to join thin disk [Mg/Fe] evolution at [Fe/H] ≈ 0. This is interpreted as mixing of delayed SNIa products (Fe-peak elements) at [Fe/H] $= -0.3$ and the on going star formation in the thick disk.

Reddy *et al.* (2006) proposed an alternative scenario from the much larger sample of stars at given [Fe/H]. Inspection of the Figure 1 reveals a few thick disk stars (13) following thin disk abundance pattern. These stars are shown in Figure 1 as red symbols embedded in black circles. We called them TKTA stars (Thick disk Kinematic and Thin disk Abundances). As shown in Figure 1 there are equal number of TKTA stars on either side of the "Knee" (or at [Fe/H] = -0.3). The TKTA stars below [Fe/H] $= -0.3$ complicates the claim by Feltzing *et al.* It is very unlikely that these stars are mistakenly identified as TKTAs. This may suggest TKTA stars form a single relation implying chemical evolution of thick disk ends at around [Fe/H] = -0.3 and the SNIa contribution to thick disk evolution is minimal. Ramirez *et al.* (2007) also come to similar conclusion from Non-LTE study of oxygen abundances of 523 stars. Origin of TKTA stars is yet to be established. Are TKTA stars run away low mass stars? Are TKTA stars belong to thin disk but heated to acquire thick disk kinematics? or They belong to one of the moving clusters in the Galactic disk? Much larger sample of stars with very accurate information of kinematics and abundances may answer above questions.

2.3. *Origin of the Thick Disk*

The issue of thick disk was subjected to many theoretical studies recently. One school of thought is that the thick disk was formed by heating of the already formed thin disk by way of mergers (see Quinn, Hernquist & Fullagar (1993). However, the observed large difference in drift velocities between thin and thick disks is difficult to explain by heating thin disk as the change in angular momentum by heating is not significant. Another scenario is that thick disk contains stars directly captured from satellite galaxies during the mergers (Abadi *et al.* 2003) or thick disk formed through multiple mergers involving gas-rich systems invoking early star formation and simultaneous heating (Brook *et al.* 2005). It may be possible that all of the above scenarios are responsible for the creation of thick disk.

Results on thin and thick disk are used to characterize evolution of the Galactic disk. Thick disk stars are older (9-13 Gyrs) having an age range of about 3-4 Gyrs (Figure 2). Models in the frame work of ΛCDM universe predict very high rate of mergers in the past say beyond a redshift $z \sim 1$ or about 8 Gyrs ago. Thus, history of mergers may explain why the thick disk stars are older. The evolution of the disk is sketched in Figure 2. Tracks A to B represent evolution of thick disk with dominant contribution from SNII. Point B corresponds to [Fe/H] = -0.3. The metal rich gas of thick disk might have been diluted by gas-rich metal-poor dwarf galaxy (satellite galaxy) to reach a point C ([Fe/H] ≈ -0.7) in our scheme of evolution (see Figure 2). Point C may represent the initial composition of thin disk. The jump C-D may be interpreted as due to mixing of delayed

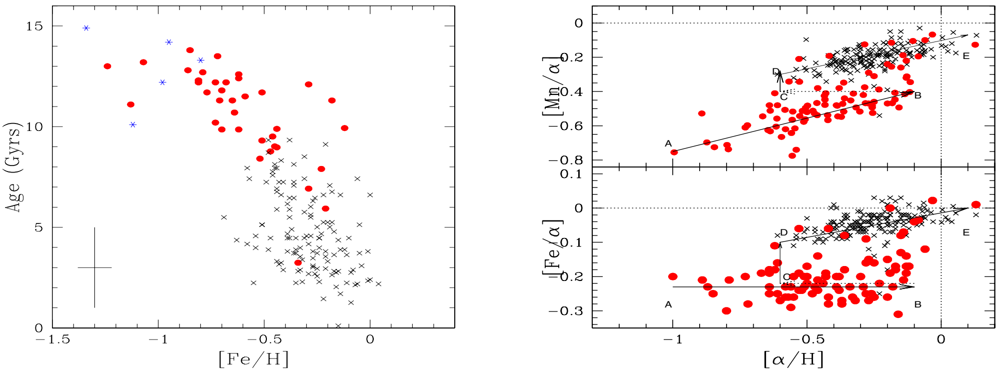

Figure 2. *Left panel*: Plot of age versus metallicity for stars of thin disk (crosses) thick disk (filled circles) and halo (star) components. *Right panel*:

SNIa products. Finally, track D-E corresponds to the evolution of a new thin disk with contribution from SNII, SNIa, and AGB stars.

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Discussion

Thomas: Are those systematic differences between the various α-elements?.

Reddy: Yes they do. [Mg/Fe] values are significantly higher compared to [Si/Fe], [Ca/Fe] and [Ti/Fe]. Also [Ti/Fe] ratios are higher compared to Si and Ca. They also differ in the trends. This may suggest all α-elements are not produced in same amounts relative to Fe.

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