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The Role of the Stellar Chemical Evolution Models in Galactic Research

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ABSTRACT
Galactic chemical abundance gradients may help us to understand the formation and evolution of galaxies. Early-B and late-F type stars are often used to construct these gradients, because the photosphere of these stars is generally well-mixed by convection or stellar wind. The photosphere of the other stars might be affected by diffusion and their spectral features may also be disturbed by magnetic field or strong wind. It is essential to use realistic model atmospheres for each spectral type to obtain reliable chemical abundances. This paper first reviews the assumptions of the current model atmosphere codes and gives some examples of their bad impacts on the chemical abundances. The concept of diffusion and its related parameters are briefly explained. Some abundance analysis results are given to compare with the prediction of the current diffusion models. Current theories on the strong magnetic field of the early type chemically peculiar single stars have been discussed. Some possible solutions are suggested to take account for magnetic field and stellar wind for the the abundance analysis. A late type star with a moderate magnetic field and an early type star with a strong wind are given as examples to see how biased the derived abundances are.

1. Introduction

Most information needed to trace the galactic chemical abundance gradient come from the stars. In this paper, we discuss the assumptions of modelling stellar atmospheres and the current situation of the stellar chemical evolution models.

2. What Spectral Types Can Be Used to Trace Galactic Abundance Gradient?

Stars are the key objects to trace galactic abundance gradient. However, we cannot use the stars with any spectral type for this purpose. We need stars with photospheres well mixed with their

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interiors. For a galactic study, our aim is to reveal the chemical composition of the birthplaces of the stars rather than the chemical compositions of the stars.

WR and O type stars have strong stellar winds. As the wind may affect the line profiles, it should be carefully taken into account in the chemical abundance analysis. However, early B-type main sequence stars might be use to trace the pristine chemical abundances (i.e., the abundance of the birthplace of the star), as the material in their photospheres is mixed by moderate winds. The atmospheres of late-B, A and early-F type stars might be strongly affected by atomic diffusion. As the diffusion can change the photospheric composition, the photospheric abundances might not reflect the pristine abundances. Moreover, the early type stars, in general, do not have large number of metallic lines in the optical region of their spectra and the abundances of only limited number of species can then be derived.

Late-F type stars have large convective envelopes which mixes the outer layers of the stars well. These objects might thus be the best objects to trace galactic abundance gradient. G and later type stars might have strong magnetic field. As the magnetic field can affect the certain line profiles, the conventional model atmospheres and line formation codes may not reflect the photospheric abundances of these stars correctly. The optical spectra of the K and M type stars also strongly affect by molecular bands and line blending which make the spectral analysis quite difficult. Consequently, early-B type main-sequence stars, F-type dwarfs/giants, and non-magnetic early-G type stars can reflect the chemical abundances of their birthplaces better than the other types. Particular treatments are needed for the object with other spectral types.

3. What Model Atmospheres Can Be Used?

There are many model atmosphere and line formation codes are available these days. For stars with intermediate and late spectral types, e.g., ATLAS (Kurucz, 1970), MARCS (Gustafsson et al., 2008), PHOENIX (Allard & Hauschildt, 1995), and CO5BOLD (Freytag et al., 2002) can be used. For hot stars, e.g., DETAIL/SURFACE (Buttler & Giddings, 1985), CMFGEN (Hillier & Miller, 1998), FASTWIND (Puls et al., 2005), TLUSTY (Hubeny, 1988), and POWR (Gräfener et al., 2002) can be used. Figure 1 shows the effective regions of these model atmosphere codes. The effective temperature and surface gravity interval of the grids of these models indeed covers almost the entire Hertzsprung-Russell (HR) diagram. However, this does not mean that we solve all problems of stellar atmosphere modelling, since the assumption of these codes may cause uncertainties in the derived chemical abundances.

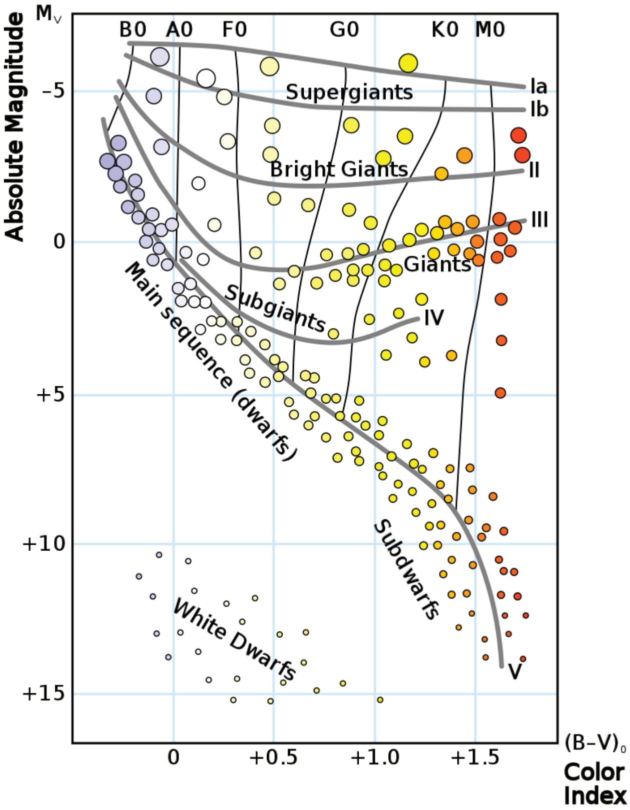

Figure 1. Effective regions of the model atmospheres on Hertzsprung-Russell diagram.

Table 1. Some model atmosphere codes sorted by their assumptions.

	Local Thermodinamical Equilibrium (LTE)	**Non-Local Thermodinamical Equilibrium (Non-LTE)**
Plane Parallel Atmosphere	ATLAS	TLUSTY DETAIL/SURFACE
Spherical Atmosphere	MARCS	PHOENIX POWR (wind modeling) FASTWIND (wind modeling) CMFGEN (wind modeling)
Box	CO5BOLD	

Table 1 summarizes some of these assumptions used by the various model atmosphere codes. As a good example to emphasize the importance of these assumptions, Reddy & Lambert (2017) have recently reported a problem related to the Ba abundances. It is well-known that the Li abundance of the stars reduces by age, as Li is rapidly depleted in the stellar atmospheres by certain nuclear reactions. A similar behavior seems to be present also for Ba element, but it is not possible to explain it by nuclear scenarios. For instance, s-process fails to explain the phenomenon, because the abundance of the other s-process elements, such as La, Ce, Nd, and Sm, do not show a remarkable change with age. Reddy & Lambert (2017) concluded that the derived Ba overabundances for very young stars might not be physically real and they might arise from the microturbulent velocity approximation and/or neglected effect of the magnetic field. This simple example shows how the assumptions of the model atmospheres and/or line formation codes can disturb the derivation of the abundances.

4. Atomic Diffusion and Stellar Chemical Evolution Models

Atomic diffusion in stars basically involves three main processes:

- Gravitational Sedimentation
- Radiative Levitation
- Mixing Mechanisms
    - Convection
    - Meridional circulation
    - Turbulence
    - Mass loss / stellar winds
    - Accretion
    - Rotational mixing
    - Magnetic field
    - etc.

Due to the gravitational sedimentation, the heavier elements tend to sink down and the lighter ones tend to go up in the stellar atmospheres. Gravitational sedimentation become a dominant diffusion process for the stars with large surface gravity. For instance, the atmosphere of white dwarfs is generally composed by very light elements as the strong surface gravity causes large gravitational sedimentation (Landstreet, 2014).

Radiative levitation is related to the interaction between the atoms and electromagnetic radiation. Certain elements, depending on their opacities, are forced to go up in the stellar atmosphere due to the radiative levitation. In contrast to the gravitational sedimentation, radiative levitation is an active diffusion process for the stars with low surface gravity. The red giant RR Lyrae stars might be one of the good examples showing the effect of the radiative levitation. RR Lyrae stars are known as Pop II stars and they should therefore be poor in metals with respect to the young Pop I stars. However, iron abundance of the photosphere of some RR Lyrae stars seems to be as rich as those of Pop I stars, e.g., the Sun (Landstreet, 2014). This is the clear effect of the radiative levitation.

Numerous mixing mechanisms can either stimulate the effect of diffusion or, most likely, diminish it. As a result of these three processes, the chemical composition of the stellar photosphere cannot reflect the interior composition of the star. This might make difficult to research abundance gradient of the galaxies for certain spectral types.

The chemical peculiarities in the surface of the early type chemically peculiar (CP) stars are mostly correlated with atmospheric parameters, which indicates that a physical process should cause these peculiarities. The first computations of Michaud (1970) showed that diffusion can be the reason for most of these abundance peculiarities. According to these computations, typical diffusion time scale is order of 10000 years in order to move an element from the optical depth $\tau = 0.1$ to 10 (i.e., roughly 1000 km), when $F_{\mathrm{radiative}} \cong 2F_{\mathrm{gravitational}}$. Diffusion can diminish (or disappear) when a remarkable current (e.g., a mixing mechanism) is present inside the star.

The self-consistent atomic diffusion models have been published over the last decades. Turcotte et al. (1998) modelled the diffusion for F stars (with 1.1-1.5 $M_{\odot}$) using radiative levitation and gravitational settling for 28 chemical elements. Richer et al. (2000) modelled the diffusion for A stars (with 1.45-3 $M_\odot$) and included the effect of turbulence in addition to the radiative levitation and gravitational settling. Both of these studies concluded that the predicted abundance anomalies are generally much larger than the observed ones. Other hydrodynamic processes should therefore have a part in models. The effect of rotational mixing and mass loss on chemical abundances were then modeled and discussed by Talon et al. (2006) and Vick et al. (2010).

Diffusion was tested observationally by many authors (e.g., Fossati, 2012; Landstreet, 2014; Kılıçoğlu et al., 2016) using open clusters. As a conclusion, the current theoretical models can qualitatively explain the observed peculiarities in the stellar atmospheres. However, the computed quantitative abundances of diffusion models do not agree well with the observed ones in most cases. More detailed models can be necessary for an accurate quantitative analysis.

5. Abundances vs. Rotation: $v_e\sin i$ Problem

Rotational velocity of the stars can mostly be found as $v_e\sin i$, i.e., in terms of the spin-axis inclination. The angle i cannot be found in most cases, even for binary stars. There are some indirect methods to derive the angle i involving;

- Asteroseismology
- Rotation Periods
- Fourier Transforms
- Interferometry
- Starspots
- Bisectors
- etc.

For many binary stars, it might be possible to assume that the orbital inclination angle is close to the spin-axis inclination angle ($i_{\rm axis} \approx i_{\rm orbit}$). Once the spin-axis inclination is derived, the true equatorial velocities (v_e) can also be estimated. This allows us to compare the elemental abundances with equatorial rotational velocities.

To find the chemical abundances of the binary stars of SB2 type, we need to either disentangle the observed spectrum or model the composite spectrum directly. For latter, I modified the well-known SYNSPEC49/SYNPLOT code to synthesize the composite spectrum of binary stars. I (with a collaboration with M. Aydın, MSc.) also started a new project in order to derive the abundances for the components of five binary stars: Mizar A, 47 And, HD 42083, V1229 Tau and HD 169268. The effect of the rotation on diffusion will be observationally seen with the help of this project and many other projects of the other groups with similar purpose.

6. Theories of Stellar Magnetism

The magnetic field seen in the cool stars are generally explained by dynamo theory. The theory works when the both convective envelope and differential rotation are present for the star. According to the theory, faster rotation should stimulate the magnetic field. This statement has been tested by many authors, and the fast-rotating cool stars have been indeed found to exhibit larger magnetic fields (e.g., Reiners, 2012). This shows that the dynamo theory is able to explain many phenomena related to the magnetic field for cool stars. The magnetic field structure of the cool stars is often extremely complex (e.g. Brun and Browning, 2017).

The theory of the magnetic field of hot stars might be much subtler than that of the cool stars, because these stars do neither have significant convective envelope nor differential rotation. The structure of the magnetic field for these hot peculiar stars is also not as more complex as than that of cool stars: it is generally quite strong and have a bipolar structure in most cases (e.g., Silvester et al., 2014). Here, I would like to mention some key features shortly from the review of Alecian et al. (2014), regarding the fossil field theory for hot magnetic chemically peculiar (mCP) stars.

Since the dynamo theory does not work for these hot stars, the magnetic field might be a fossil. There are at least three explanation for the fossil nature of the magnetic field: i) Legacy magnetic field, ii) Merging binaries, and iii) Relaxed magnetic field. The first theory says, the galaxy may initially have a strong magnetic field (at the beginning of its evolution), and this strong magnetic field might have then been transferred to the certain molecular clouds and finally to the stars. However, this theory is inconsistent with some observations. For instance, some binary stars have only one mCP component, although both components were born in the same place. The second theory says the hot magnetic stars might be the merging binaries. Due to the conservation of the angular momentum, these stars should rotate much larger than the normal counterparts and thus trigger a large magnetic field formation. The best candidates of merging binaries are blue stragglers. However, just like normal stars, only small fraction of the blue stragglers is mCP. This is not consistent for the merging binary explanation for the magnetic field. The third theory, which is relaxed magnetic field, might be the solution to explain the strong magnetic field seen in mCP. This theory suggests that the magnetic fields of mCP stars may have been produced in convective pre-main sequence phase of the stellar evolution. When these stars start to develop convective layer, the magnetic field can still survive only if the magnetic field has a right configuration (e.g., bipolar configuration). Once the magnetic field survive, it may continue to be active at least the main sequence lifetime of the star.

The magnetic field affects many of the line profiles in the stellar optical spectrum. It strengthens them and changes their shapes/widths. For a safe chemical abundance analysis, these effects of magnetic field should be considered. EK Dra is a good observational test case to see the effect of magnetic field on the line strengths. This star has a moderate magnetic field: 66-89 G (Rosén et al., 2016). Şenavcı et al. (2019) have plotted the derived abundances for Ti, Cr, Fe and Ni elements versus the Landé g effective factor of the lines. The abundances, particularly for Cr and Ni, showed correlations with Landé g_{eff}. For the larger Landé g_{eff}, the lines tend to give larger abundances. This might be a good evidence showing that even the moderate magnetic field can disturb the chemical abundance calculation and lead overestimated abundances.

7. Extra-galactic Astronomy: Putting Wind into Context

For the other galaxies than Milky Way, in most case, we can only observe the brightest stars individually and can obtain their spectra. The most luminous stars of the spiral galaxies are blue giants and supergiants with strong stellar winds. The stellar wind not only affects the strongest lines (such as H and He lines), but also affect the lines of the metals in the optical spectra. The hot wind flow contributes the spectra forming emission lines, weakens the absorption lines and may cause underestimated abundances. In order to model the spectra of these stars and to derive the accurate chemical abundances, the wind structure of the star should be taken into account.

The easiest way to find out the wind structure of a star is theoretically modelling the most prominent lines (H and He lines) in their spectra first and derive the aeolian parameters such as mass loss and terminal velocity (e.g., HD 187983, Kılıçoğlu et al., 2016). By forming a model atmosphere using these derived parameters (e.g., using FASTWIND), the line profiles of the other elements can be correctly synthesized and accurate abundances can be derived. In this way, the abundance gradient of the many other galaxies can be obtained. For instance, Kudritzki et al. (2008) obtained the metallicity gradient of NGC 300 spiral galaxy using the early type supergiants and considering the effect of the stellar wind.

8. Conclusion Remarks

- More standardized methods are needed for chemical abundance analysis to model the chemical evolution of the galaxies: chemical abundance analysis is still a user/code depended issue.
- The uncertainties of the abundances should be carefully calculated: the standard deviation of the line-to-line abundance variation does not include systematical errors!
- More accurate abundances are needed, the assumptions of model atmospheres and/or line formation codes may lead under/overestimated abundances: Rotation, turbulence, diffusion, magnetic field, wind etc. should be carefully considered when needed.

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