THE LIMITS OF CHEMICAL HOMOGENEITY - THE CASE OF BINARY STARS

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The assumption of chemical homogeneity is a key assumption in many astrophysical studies, especially for Galactic archaeology and the methods of chemical tagging. It states that the chemical composition of the photospheres of two (or more) stars born from the same interstellar medium will remain the same for most of their lifetime. When chemically non-homogeneous binary stars are observed, this assumption is challenged. In this paper, some possible explanations for such binaries are discussed, and some example studies are presented.

OMEJITVE PREDPOSTAVKE KEMIJSKE HOMOGENOSTI - PRIMER DVOJNIH ZVEZD

Predpostavka kemične homogenosti je ključna predpostavka v mnogih astrofizikalnih raziskavah, predvsem na področju Galaktične arheologije. Na njeni podlagi predvidevamo, da kemična struktura fotosfer dveh (ali več) zvezd, ki so nastale iz enake medzvezdne snovi, ostane enaka večino njihovega življenja. Ko pri opazovanjih naletimo na dvojne zvezde, ki so kemijsko nehomogene, se poraja dvom o pravilnosti te predpostavke. V tem članku je opisanih nekaj mehanizmov, ki bi takšne dvojne zvezde razložili, predstavljenih pa je tudi nekaj raziskav, ki so se ukvarjale s to problematiko.

1. Introduction

Galactic archaeology is a field of astrophysics that studies the formation and evolution of our Galaxy. We try to understand our Galaxy's past by studying the kinematic and chemical properties of stars that we observe today.

Kinematic studies usually try to look into the Galactic past by measuring the positions and velocities of stars in the sky. These measurements, together with an assumption of the Galactic potential, enable us to integrate their orbits backwards in time. With this method, we should be, in theory, able to look as far into the Galactic past as we would like. Unfortunately, limitations arise due to our limited knowledge of the Milky Way's potential, tidal and gravitational perturbations, caused by, e.g., giant molecular clouds and spiral arms, and disruptive events, caused by close stellar encounters. Observational errors and uncertainties impose a limit as well, as they feed into the initial conditions of our calculations.

We combat these problems with complementary studies of the chemical composition of stars. If we are able to relate stars to their siblings (stars born in the same region, from the same cloud of matter[1]) by studying their chemical signatures, we can either strengthen the results of (some) kinematic studies (e.g., [1]), or even try to chemically relate stars, that are kinematically no longer related.

In Section 2 I present the chemical approach to Galactic archaeology and introduce the assumption of chemical homogeneity. I also present non-homogeneous star clusters and binary star systems, as possible evidence that the assumption is not valid. I glance over possible explanations for non-homogeneous star clusters, and focus on atomic diffusion and external pollution of stars as explanations for non-homogeneous binary stars in Section 3. In Section 4 I present some example studies on those explanations. I conclude with a brief look at possible future studies.

2. Chemical Approach to Galactic Archaeology

When determining stellar chemical composition we usually try to determine elemental abundances in the outer layers of stars. The abundance of an element is the ratio of the mass of that element

[1]Star formation occurs in clouds of matter that consist of atomic gas, molecules and dust.

in the star's photosphere,[2] to the mass of the entire photosphere. Because hydrogen and helium dominate the stellar composition, we often describe stellar composition with hydrogen and helium abundance, and metallicity - the abundance of the rest of the elements.[3] If we define hydrogen abundance as $X = \frac{m_\mathrm{H}}{M_\mathrm{star}}$, where m_H is the mass of hydrogen in a star's photosphere and M_star is the total mass of the photosphere, and helium abundance as $Y = \frac{m_\mathrm{He}}{M_\mathrm{star}}$, we can calculate metallicity (Z) as:

$$Z = \sum_{m_i > m_\mathrm{He}} \frac{m_i}{M_\mathrm{star}} = 1 - X - Y.$$

Chemical abundance ratios are sometimes used to compare the chemical structures of different stars. The abundance ratio of the elements X_1 and X_2 is defined as:

$$[X_1/X_2] = \log_{10}\left(\frac{N_1}{N_2}\right)_\mathrm{star} - \log_{10}\left(\frac{N_1}{N_2}\right)_\odot,$$

where N_1 and N_2 are the numbers of atoms of the elements X_1 and X_2 respectively and $\odot$ is used to denote the value for the Sun. Abundances are non-dimensional, but *dex*, short for *decimal exponent*, is often used in a unit-like manner. The abundance ratio of iron to hydrogen, [Fe/H], is sometimes referred to as metallicity as well.[4] If defined this way, the solar metallicity, as well as all of the other solar abundance ratios, is equal to zero:

$$[\mathrm{Fe/H}]_\odot \equiv 0,$$
$$[\mathrm{X}_i/\mathrm{H}]_\odot \equiv 0.$$

2.1 Chemical Homogeneity

We can use acquired data on stellar chemical compositions to determine their origin. To do this, we assume that stars, made from the same cloud of matter, will all have the same chemical signature when observed. This might seem like an unreasonable assumption, as stars are active systems with constant fusion that could enrich the star with heavier elements. However, while some stellar layers are convective, in every star with mass greater than half of the Solar mass, there is the so-called radiation zone, where the energy is transported almost exclusively by electromagnetic radiation.[5] Energy transfer by convection in this zone is negligible because the pressure gradient is so high, that the adiabatic expansion of rising gas lowers its density less than the local drop of density, so the gas sinks again. We write this condition as:

$$\left.\frac{d\rho}{dr}\right|_\mathrm{ad} < \left.\frac{d\rho}{dr}\right|_\mathrm{local}, \qquad (1)$$

where $\frac{d\rho}{dr}$ is the radial derivative of the density of the gas. We can differentiate the adiabatic relationship between pressure and density to express the left hand side of Eq. (1) in terms of pressure and temperature, and then differentiate the ideal gas law to express the right hand side of Eq. (1) with the same quantities.[6] The resulting equation is the criterion for stability against convection:

$$\frac{dT}{dr} > \frac{T}{P}\left(1 - \frac{1}{\gamma_\mathrm{ad}}\right)\frac{dP}{dr},$$

[2] A star's photosphere is the star's transparent outer layer.

[3] In astronomy and astrophysics all elements heavier than helium are referred to as metals.

[4] Iron is a good element to use as a proxy for metallicity because it has a lot of spectral lines over the whole spectrum, making its abundance easy to measure.

[5] The size and location of the radiation zone are heavily dependent on the star's mass. I discuss this a bit more in depth in Section 3.2.2.

[6] A more detailed approach can be found in [2].

where P is the pressure, T the temperature, and γ_{ad} the adiabatic index of the gas. Because of this non-convective zone, fusion products are trapped inside the stellar core and not brought up to the surface of the star. Different fusion processes in stars with varying masses should therefore not affect the chemical composition of those stars' photospheres.

If this is indeed the case, we can chemically relate (chemically tag) stars that were born from the same cloud of matter. This provides a strong tool for researching the Galactic past.

2.2 Non-Homogeneity in Star Clusters

Star clusters are gravitationally bound groups of a few hundred to a few million stars with origin in the same (large) cloud of matter. According to the assumption of chemical homogeneity, we would thus expect them to have the same chemical structure. While some evidence for non-homogeneity in stellar clusters has been presented (e.g., [3]), it is not fatal to the assumption of chemical homogeneity, as there are viable explanations for non-homogeneity on larger scales.

The most obvious one is the inhomogeneity of clouds of matter. Because star clusters are large structures (up to a few hundred light-years), they form from vast clouds of matter that can be inhomogeneous on large scales. We can also observe chemical non-homogeneity in clusters with stars of multiple populations [4]: as some more massive stars from the original star-forming era explode in a supernova, new stars can be born from this new, more metal-rich interstellar medium. We then observe stars made from this recycled material as well as the original stars and see different chemical signatures.

2.3 Non-Homogenous Binary Star Systems

Binary star systems (binary stars, binaries) are systems of two stars that are gravitationally bound and orbiting each other (Fig. 1). We can be almost sure that both stars in a binary system were born from the same area inside a cloud of matter, because the probability that two stars from different stellar nurseries (areas with a high rate of star formation) would interact and become gravitationally bound is extremely small. Because all of the mechanisms discussed in Section 2.2 that would explain non-homogeneity in star clusters rely on non-homogeneity of initial conditions due to large spatial scales, we cannot use them to explain non-homogeneity in binary stars. However, we do observe binary stars that are chemically non-homogeneous (e.g., [5, 6]), so it is reasonable to start doubting the validity of the assumption of chemical homogeneity.

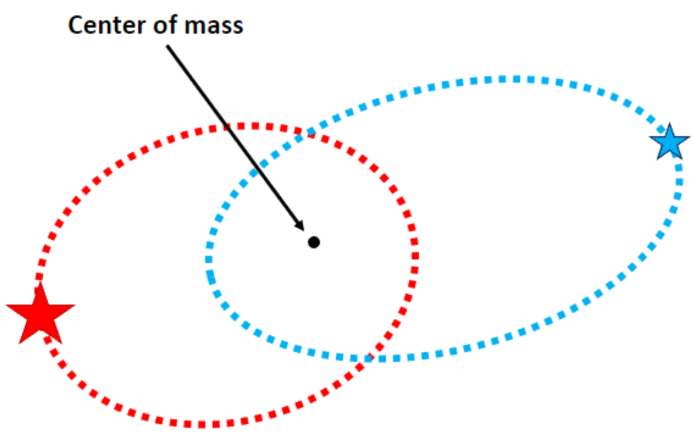

Figure 1. A scheme of a binary star system. Inspired by a similar scheme from [7].

3. Possible Explanations for Chemically Non-Homogeneous Binary Stars

Because the assumption of chemical homogeneity is such a key assumption in so many studies, trying to find logical explanations for non-homogeneous binaries is a logical next step. While we have ruled out the transfer of metals from the stellar core by convection, there might still be other effects that could cause such a transfer. There could also be some effects that would bring metals from stellar surroundings onto the star. In this case, the metals would be absorbed in the stellar photosphere and no additional element transfer mechanism from the core would be required.

3.1 Atomic Diffusion in Stars

Inside stars, multiple effects influence the movement of atoms. But when it comes to the chemical evolution of the photosphere, we are only interested in effects that transfer atoms anisotropically in the radial direction, so thermal diffusion, for example, will not interest us at the moment. When considering mechanisms that could influence an atom to travel either towards the stellar core or away from it, the two prevailing effects are gravitational settling and radiative acceleration. Gravitational settling is the net effect of gravitational and buoyant force and causes heavier elements to drift towards the core. Radiative acceleration is caused by photons propagating from the stellar interior towards the surface of the star. We can roughly estimate it to be proportional to the radiative pressure P_{rad}, the cross-section of the atom σ_{atom} for photon interaction, and inversely proportional to its mass m_{atom}:

$$a_{\mathrm{rad}} \propto \frac{P_{\mathrm{rad}}\sigma_{\mathrm{atom}}}{m_{\mathrm{atom}}} \propto \frac{T_{\mathrm{local}}^4\sigma_{\mathrm{atom}}}{m_{\mathrm{atom}}}.$$

The cross-section for photon-atom interaction is dependent not only on the element, but also on the atom's excitation and ionization state. Hence, different elements will experience varying radiative acceleration, thus traveling towards the photosphere with different velocities and possibly changing the observed chemical composition.[7] Furthermore, the ratio of atoms of an element in different ionization and excitation states is reliant on the local temperature of the gas. This, combined with the fact that temperature radial profile of a star is strongly reliant on the star's mass, could cause atomic diffusion to influence the observed chemical composition differently in stars of different mass.

3.2 External Pollution

If the cause for non-homogeneity are not processes inside the star, the other obvious option is pollution from its surroundings.

3.2.1 Interacting binary stars

In a binary system, it is possible—provided the stars orbit each other at a sufficiently small distance—that material flows from one star onto the other. However, this happens most commonly in systems of stars at late evolutionary stages: one being in its giant phase, while the other has already become a white dwarf. During a star's expansion into a giant, after it has depleted its core of hydrogen and hydrogen fusion can no longer be supported, its convective envelope deepens until it reaches the core. This causes fusion products to mix into the star's photosphere and change the observed chemical composition. This is *the first dredge-up*. During the star's further evolution, two more similar processes, connected to the fusion of helium, can occur.[8] When the

[7] A more formal and detailed approach can be found in [8].

[8] They are called *the second* and *the third dredge-up*. A more detailed explanation on all three dredge-ups can be found in [2].

star then evolves into the white dwarf phase, it blows its envelope away completely. This makes interacting binary stars, consisting of a white dwarf and a giant, not as interesting as other binary stars when studying their chemical homogeneity, because the presumption that evolution does not influence a star's chemical composition strongly is no longer correct. Additionally, because a star in its giant phase is much brighter than the white dwarf, it is almost impossible to measure their stellar compositions separately.

3.2.2 Planet-Pollution

Around 50% of stars have planets [9, 10], many of them more than one. The properties of those systems, such as the number of stars in the system, eccentricities of their orbits and their masses, can vary widely, so it is expected that their dynamical histories are diverse as well [10]. So when we are presented with evidence of planets in highly eccentric orbits [11, 12], as well as rogue exoplanets (planets not orbiting a star) [13], it is an indication of intensive planet-planet or planet-star interactions that could cause some planets to plunge into their parent star. This could be a source of external pollution that would change a star's chemical composition and could be a reason for (some) non-homogeneous binary star systems.

Stars are much more massive than planets—the most massive planet in the Solar system, Jupiter, is about 1000-times less massive than the Sun—so ingestion of a planet into a star might seem negligible. However, like in Section 2.1, the importance of a star's radiative layer is demonstrated again. If a Jupiter-like planet plunged into a Sun-like star with no radiative zone and was fully convective, its metallicity would increase by (assuming that Jupiter consists of 10% metals—thus being 10x as metal-rich as the Sun—and that hydrogen influx is negligible):

$$\Delta[Z/\mathrm{H}] = \log_{10}\left(\frac{N_{Z,\star}+N_{Z,\mathrm{Jup}}}{N_\mathrm{H}}\right) - \log_{10}\left(\frac{N_{Z,\star}}{N_\mathrm{H}}\right)$$

$$\Delta[Z/\mathrm{H}] = \log_{10}\left(\frac{N_{Z,\star}+N_{Z,\mathrm{Jup}}}{N_{Z,\star}}\right) = \log_{10}\left(1+\frac{N_{Z,\mathrm{Jup}}}{N_{Z,\star}}\right)$$

$$\Delta[Z/\mathrm{H}] \approx \log_{10}\left(1+\frac{10\frac{m_\mathrm{Jup}}{m_\star}N_{Z,\star}}{N_{Z,\star}}\right) \approx \log_{10}\left(1+10\times\frac{1}{1000}\right) \approx 0.004\,\mathrm{dex}.$$

In the calculation above, I used Z to denote all metals, Jup to denote the Jupiter-like planet, and $\star$ to denote the Sun-like star before the impact.
While 0.004 dex abundance change is too small to be reliably detected by current studies (usual uncertainties of regular precision studies are $\sim$ 0.01 dex [14]), the actual 0.09 dex [15] change that would occur if Jupiter would pollute the Sun's outer convective layer is completely realistic to observe.[9] The fact that it is only the star's convective envelope the planet is absorbed into is very important because the thickness of a star's convective layer is heavily reliant on its effective temperature[10] (T_eff). Stars with lower T_eff have larger convective zones: a star with $T_\mathrm{eff} \lessapprox 3700$ K or mass of about 0.5 $\mathrm{M}_\odot$ will be completely convective, then the convective zone will shrink with rising mass and temperature, and a star with $T_\mathrm{eff} \gtrapprox 7500$ K and mass of about 1.5 $\mathrm{M}_\odot$ will have convective core and radiative outer layers (Fig. 2). This causes hotter, more massive stars to be much more sensitive to any accretion of material, as the effective mass that a planet will mix into becomes smaller with increasing stellar mass.

[9] It is interesting to note that the mass of the Sun's convective envelope is only around 1-2% of the Sun's entire mass [15], while stretching from 60% of the Sun's radius to its edge.

[10] A star's effective temperature is the temperature that a black body radiating the same power would have.

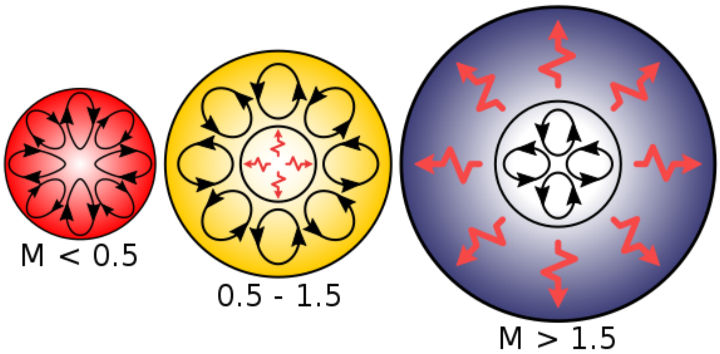

Figure 2. Convective and radiation zones in stars of different masses. Values under stars are the star's mass in units of solar masses. Black ellipses mark the convective zone, red arrows the radiation zone. From [16].

4. Example Studies

So far, I have presented possible explanations for chemical non-homogeneity. It makes sense to take a look at some studies that have been conducted so far.

4.1 Atomic Diffusion

Two studies, one conducted by C. Bertelli Motta et. al. in 2018 [17], and the other by D. Souto et. al. in 2019 [18], both researched atomic diffusion in star cluster M67. The 2018 study analyzed abundances of up to 12 elements in 15 single stars (not binary stars) and compared them with models of stellar evolution. They concluded that due to atomic diffusion, chemical tagging is limited to the order of ~ 0.1 dex. Similarly, the 2019 study analyzed abundances of 15 elements in 83 single stars and compared them to theoretical models. They concluded that atomic diffusion dominates abundance changes in stars until they reach their (sub)giant phase when the first dredge-up process occurs.

A 2021 study by F. Liu et. al. [3] searched for evidence of atomic diffusion solely in binary star systems. They analyzed high-resolution spectra of 7 binary stars and found that their models of atomic diffusion agreed with observational evidence, and concluded that atomic diffusion is non-negligible (it caused abundance difference of up to 0.07 dex within a binary system). They also searched for evidence of non-homogeneity induced by planet formation. In this scenario, planets would form mostly from metals in the stellar surroundings during stellar formation. The star would consequently be able to accrete fewer metals during formation and become less metal-rich.[11] They did, however, not find enough evidence to make any solid conclusions regarding this effect.

4.2 Planet Pollution

A 2001 study by M. H. Pinsonneault et. al. [15] searched for evidence of accreted planetary material in Sun-like stars. They studied metallicities of 33 stars with confirmed planets and searched for a possible correlation between a star's temperature and its metallicity. They did not find the expected correlation and concluded that the accretion of planets onto stars is unlikely, as long as the probability that a star accretes a planet is not strongly related to that star's mass. They did, however, state that their findings do not exclude accretion of less than one Earth's mass of planetary material or infalls of massive planets that would penetrate a star's convective layer.

[11] This is a scenario that is completely separate from planet-pollution discussed in Section 3.2.2.

On the other hand, three recent studies, one conducted by T. Nagar et. al. in 2019 [14], and two conducted by L. Spina et. al. in 2018 [19] and 2021 [20], present results that are much different. The 2018 study conducted in the star cluster Pleiades found chemical anomalies that "could be explained by planet engulfment events"[19]. The 2019 study conducted on 14 binary systems found, to date, the most non-homogeneous binary system (0.19 dex difference in metallicities) and concluded that at least one of the stars in the system was polluted by a rocky planet. Even stronger evidence for planet pollution was found in the 2021 study. That study, conducted on 107 binary systems of Sun-like stars, researched chemical anomalies in binary systems, related to their average T_{eff}. It found that systems with higher T_{eff} were more likely to be chemically anomalous. This is expected if planet-pollution occurs, because the size of the photosphere, in which a planet dissolves, decreases with rising T_{eff}. They argue that the mean probability for planet engulfment in a Sun-like star is 0.27, with 90% confidence interval equal to 0.20–0.35.

5. Conclusion

The assumption of chemical homogeneity is a key assumption in many astrophysical studies, especially in the field of Galactic archaeology. It states that stars made from identical material will stay chemically identical throughout their lifetimes. So when we are presented with non-homogeneous stars in clusters or binary systems, for which we think are made from the same material, we need to either challenge the assumption or find an explanation for those systems. Non-homogeneity can be explained by either processes of stellar evolution, or by external pollution. In this paper such processes and some example studies are reviewed.

Atomic diffusion has been found to significantly alter the chemical compositions of stars, enough to be non-negligible when observing binary systems [3]. Strong evidence for external pollution of stars due to the engulfment of planets has also been presented in recent years, with 27% of Sun-like stars now presumed to have ingested a planet, according to a 2021 study by Spina et. al. [20]. These two effects can provide chemical inhomogeneities up to 0.07 dex [3] and 0.19 dex [14], respectively.

Because we can explain chemical inhomogeneities in binary systems by the well understood effects discussed in this paper, the assumption of chemical homogeneity can remain a strong tool in astrophysical studies. Furthermore, if the assumption of chemical homogeneity holds, we could use acquired data on atomic diffusion to better understand the evolution of diffusive effects inside stars. With data on planet engulfment events, we could study chemical compositions of ingested planets and even look for those with compositions similar to that of the Earth.

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