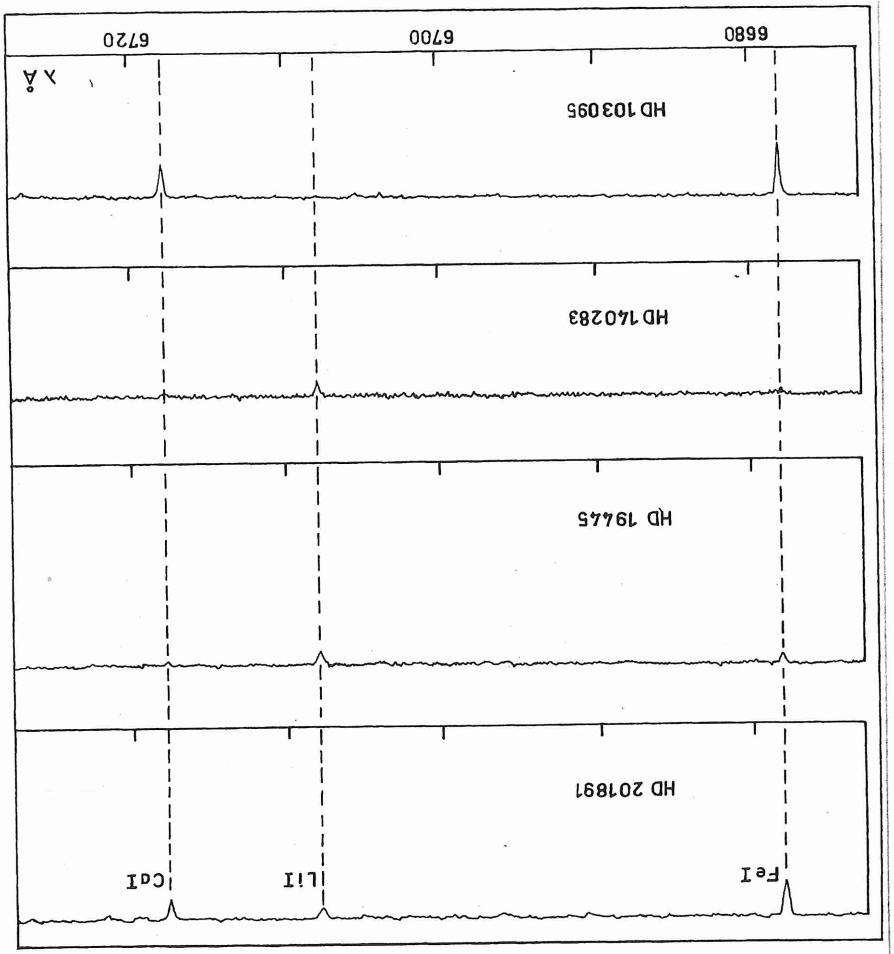
Li/H ≡ ^{7}Li/H

- WAGONER et al. (1967) first suggested ^{7}Li from BIG BANG and compared predictions with meteoritic Li (then, ONLY data point)
- BOESGAARD's 1976 ARAA review noted Li in warmest stars of open clusters ≅ meteoritic Li. Asked: is this like primordial Li abundance?
- THEN, Spite & Spite (1982) found Spite plateau for warm metal-poor stars $\log\epsilon(\text{Li}) = 2.05$



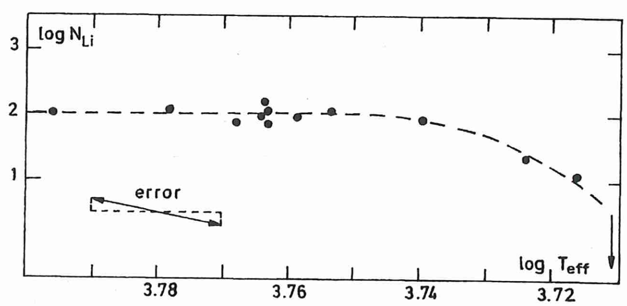


Fig. 5. N_{Li} versus log T_{eff} for old halo stars

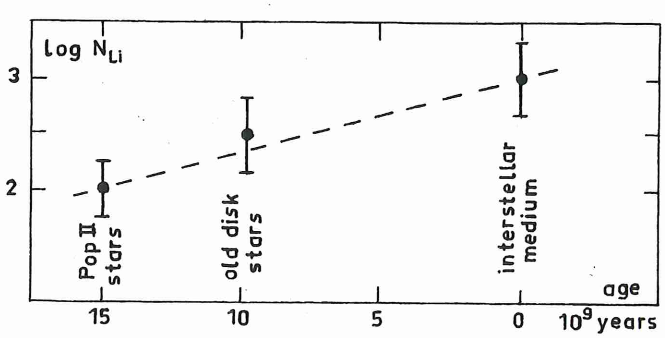
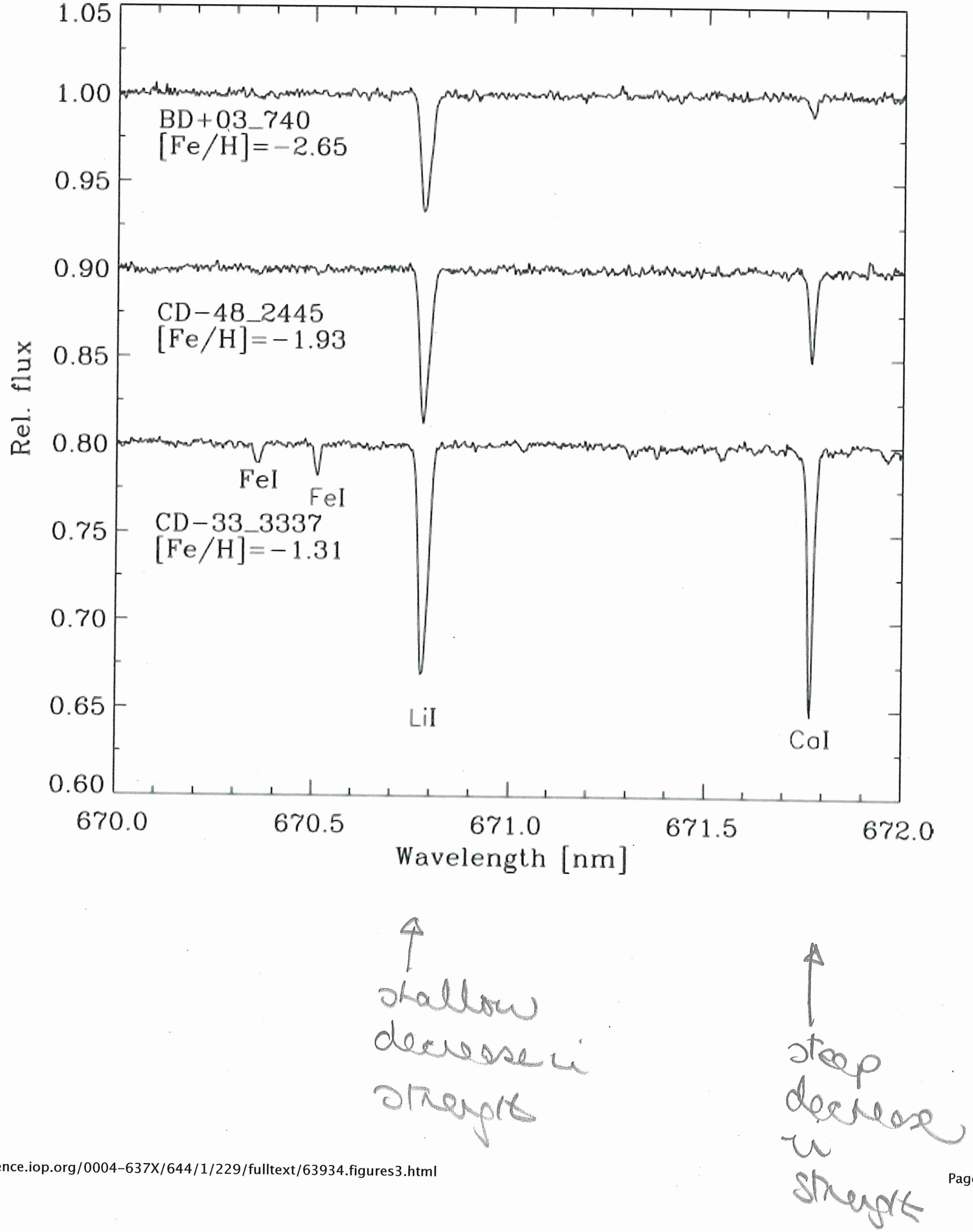


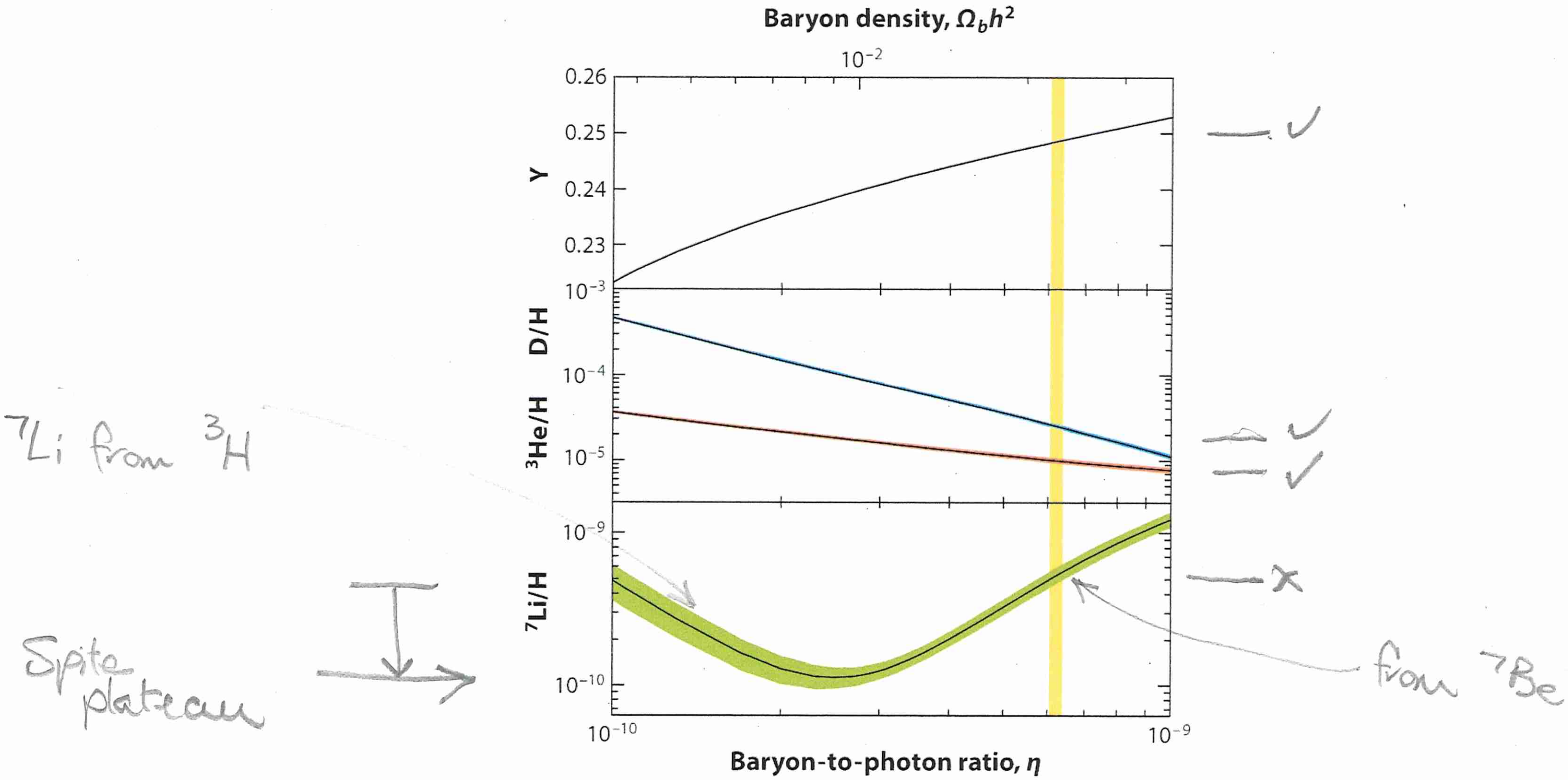
Fig. 6. Evolution of the Li abundance during the life of the Galaxy

Fig. 3

CITED IN TEXT | HIGH-RESOLUTION IMAGE (126 kB) Go to: Figure 2 | Figure 4

Sample spectra around the Li I 670.8 nm line with the spectra of CD -48 2445 and CD -33 3337 shifted 0.10 and 0.20, respectively. Note that the region between the Li I and the Ca I lines in the spectrum of CD -33 3337 is affected by several faint lines, which are not identified on the figure.





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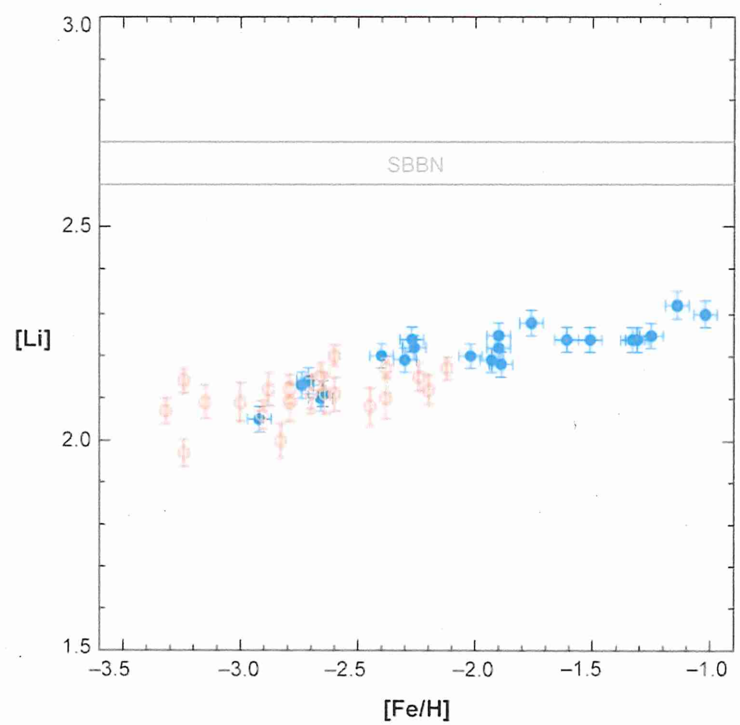

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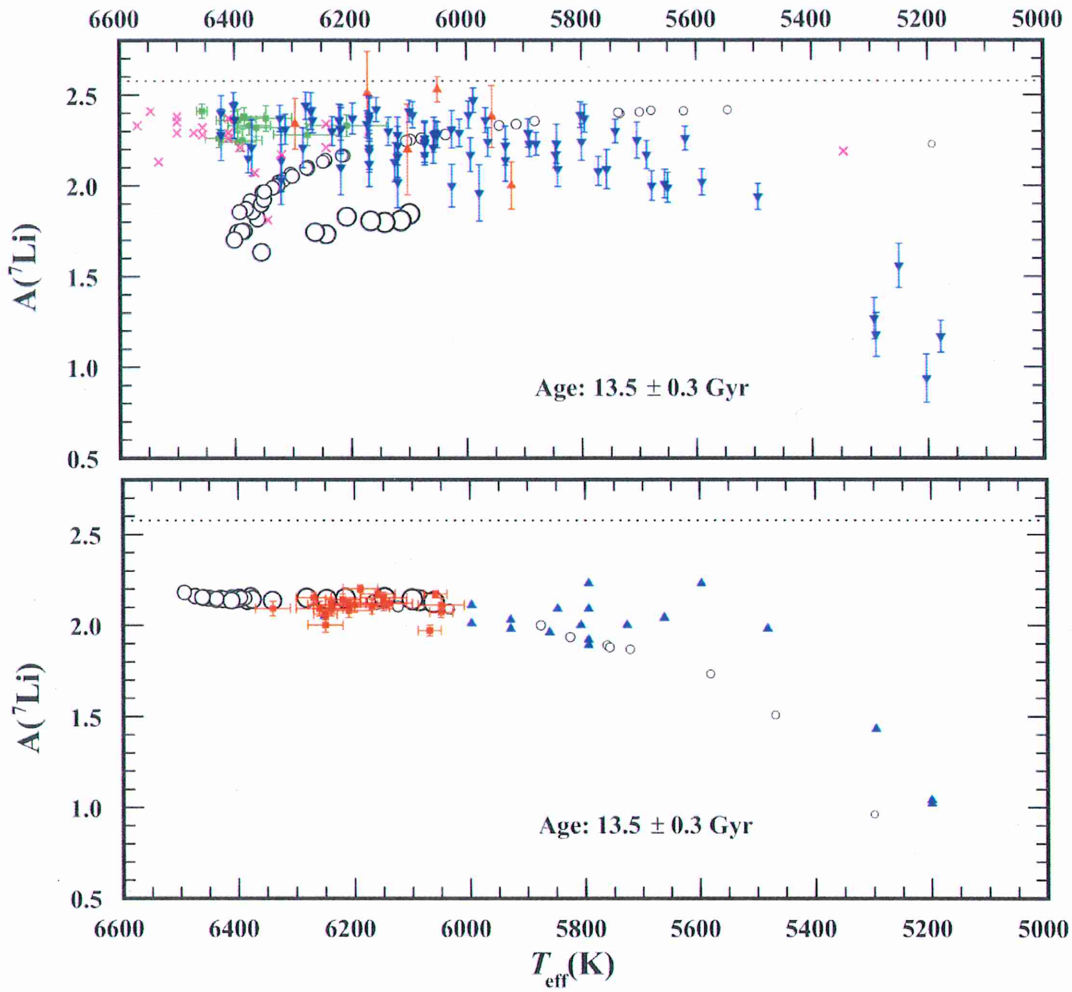

FIG. 8.—Predicted Li abundance in stars without turbulence (*top*) and with the T6.25 turbulence (*bottom*). For the calculations, the initial value of $A(^7\mathrm{Li})$ is 2.58 and open circles are used. The size of the circles is a function of the radius of the stars in order to roughly indicate their evolutionary stage. There are 50 simulated stars in each panel and 90% of them are between 13 and 14 Gyr. Further description is found in the text. Also shown are observations in metal-poor halo stars in the upper panel by Thorburn (1994; *blue triangles*), Bonifacio et al. (2005; *magenta crosses*), Bonifacio et al. (2002; *green squares*), Bonifacio (2002; *red triangles*), and in the lower panel by Spite et al. (1984; *blue triangles*) and Ryan et al. (1999; *red squares with error bars*).

ApJ 619 538 2005

Not quite ab initio!

but the upward diffusive term is increased and cancels the downward advective term for a very small abundance gradient, limiting surface underabundance to −0.22 dex. With T6.09 turbulence, it is limited to −0.19 dex, again with little additional burning. As turbulence is further increased to T6.25, however, additional burning occurs.

Atomic diffusion is thus largely responsible for the transport of ^{6}Li and ^{7}Li immediately below the surface convection zone not only in the model with atomic diffusion but even in the T6.25 model. The transport by atomic diffusion determines the reduction of $^6\mathrm{Li}/^7\mathrm{Li}$. Even when turbulence reduces the effect of atomic diffusion for metals below 0.1 dex, atomic diffusion is still the dominant transport process for ^{7}Li below the surface convection zone. We have also verified (not shown) that, in the absence of atomic diffusion, the surface $^6\mathrm{Li}/^7\mathrm{Li}$ abundance reduction is dominated by turbulent transport and the reduction factor does not approach the value of equation (4) with $r \approx 90$. It is only when one assumes instantaneous mixing between the Li-burning region and the surface that the reduction factor approaches this value. This is appropriate, for instance, on the pre-main sequence (Proffitt & Michaud 1989). Otherwise, the transport mechanism, be it atomic or turbulent diffusion, plays the dominant role in determining the surface reduction factor.

4. DISCUSSION

4.1. Li *Abundance and Upper Limits to Turbulent Transport*

In Figure 8, calculated surface abundances are compared with observations of Li in halo stars and in two globular clusters. On the upper part of Figure 8 is shown the calculated surface Li concentration (*open circles*) in 50 stars of initial metallicity $[\mathrm{Fe/H}] = -2.31$. These are the result of a Monte Carlo simulation based on interpolations among a dozen complete evolutionary tracks (see Fig. 15 of Richard et al. [2002a] for the results of a different draw in which [Fe/H] was also allowed to vary). No turbulence is assumed outside of convection zones. The age of stars was randomly generated around 13.5 Gyr with a Gaussian distribution of 0.3 Gyr standard deviation; 90% of the generated stars are between 13 and 14 Gyr. Only stars with $\log g \geq 3.8$ are included. Observations of Li abundance in metal-poor halo stars by Thorburn (1994), in very metal-poor stars by Bonifacio et al. (2005), and in the globular clusters M92 and NGC 6397 (Bonifacio 2002; Bonifacio et al. 2002) are also shown. The Li observations below 5500 K may have been affected by pre-main-sequence evolution (see Fig. 3, *top*), which might explain the lower Li abundances observed in those stars. However, it does not appear possible to

See also Gruyters et al. A&A 567 A72 (2014) and refs. therein

New Abundances for Old Stars – Atomic Diffusion at Work in NGC 6397

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A homogeneous spectroscopic analysis of unevolved and evolved stars in the metal-poor globular cluster NGC 6397 with FLAMES-UVES reveals systematic trends of stellar surface abundances that are likely caused by atomic diffusion. This finding helps to understand, among other issues, why the lithium abundances of old halo stars are significantly lower than the abundance found to be produced shortly after the Big Bang.

When Joseph Chamberlain and Lawrence Aller in 1951 announced the discovery of stars significantly more metal-poor than the Sun, a new field of astronomical research was born: the observational study of nucleogenesis (or cosmochemistry) which attempts to answer the question of where the chemical elements come from and how their build-up proceeds with time. Today, while many details remain unsettled, we have a general understanding of how the cosmos developed chemically, from a mixture of hydrogen, helium and traces of lithium a few minutes after the Big Bang to stars as metal-rich as the Sun and beyond. The majority of this knowledge has been gathered by studying starlight by means of quantitative spectroscopy. Solar-type stars (here defined to be stars of spectral types F, G and K) have always played a central role in cosmochemical studies, primarily for two reasons: they have rich photospheric spectra (allowing a great variety of elements to be studied) and are long-lived (allowing all phases of Galactic chemical evolution to be investigated).

The art of deriving chemical abundances from spectra is to relate the observed line strengths of a certain element to its abundance in the stellar atmosphere these lines originate in. This is achieved by capturing the essence of the matter-light interaction in a theoretical model. To make this problem computationally feasible, a number of assumptions about the physics of stellar atmospheres are introduced: the atmosphere is assumed to be well represented by a one-dimensional and static temperature and pressure structure in local thermodynamic equilibrium (LTE), convection is treated according to the mixing-length recipe, rotation, mass loss and magnetic fields are disregarded all together. All these are traditional assumptions, to mention only the most obvious ones. Some of these have in the meantime been abandoned, but many analyses still rest on them and are adorned with the flattering title 'classical analysis'. One less explicit assumption often made when interpreting the abundance results concerns the chemical abundances themselves: they are assumed to be representative of the material the star originally formed out of. This means in particular that there are no physical processes which alter photospheric abundances with time.

It comes with the profession of a theorist to question the (sometimes bold) approximations made by more observationally inclined astrophysicists. Lawrence Aller, Evry Schatzmann and others addressed the problem of atomic diffusion already in the 1960s. Later, when a common abundance of lithium was found among warm halo stars by Monique and François Spite (1982; the so-called Spite plateau) and interpreted as a relic of the Big Bang, Georges Michaud and colleagues presented models of stellar evolution with atomic diffusion that "change the lithium abundance by at least a factor of about two in solar-type stars". Larger effects were predicted for Population II stars. In other words, this study showed that lithium and other elements slowly settle into the star under the force of gravity. In particular for old stars the assumption of the constancy of photospheric abundances seemed questionable.

Models with atomic diffusion were subsequently shown to be very successful in reproducing the abundances of hot, chemically peculiar (CP) stars. The significance of diffusion for solar-type stars has, however, been seriously questioned: predicted effects from early models were quite large and failed to, e.g., meet the observational constraint of a flat and thin Spite plateau of lithium (Ryan et al. 1999). This problem has been alleviated in recent years by including additional effects like radiative levitation and turbulent mixing which counterbalance gravitational settling.

Putting diffusion in solar-type stars to the test

Globular clusters of the Galactic halo are primary testbeds for stellar evolution theory in general and for effects of atomic diffusion in particular. Stars in globular clusters have the same age and initial composition (with certain exceptions). To test the atomic-diffusion hypothesis, one thus compares photospheric abundances of stars at the main-sequence turnoff (where the effects of diffusion are largest) to the abundances of red giants (where the original heavy-element abundances are essentially restored due to the large radial extent of the outer convection zone). What sounds like a straightforward measurement in theory is challenging in practice: at a magnitude of 16.5^{m}, turnoff stars in one of the most nearby globular clusters (NGC 6397, see Figures 1 and 2) are too faint to analyse on 4-m-class telescopes at high resolution and high signal-to-noise (S/N) ratio. It took the VLT and the efficient spectrograph UVES to analyse these stars for the first time.

When UVES became available in the late 1990s, there were two teams that focussed their efforts on NGC 6397. Raffaele Gratton and co-workers wanted to further constrain the nature of the anti-correlations of certain elements commonly found among giants by looking for them in unevolved stars. Frédéric Thévenin and colleagues investigated the connection between globular clusters and halo field stars as regards alpha-capture elements. Two different metallicities were advocated for the cluster by these two groups, $\log \varepsilon(\mathrm{Fe}) = \log (N_{\mathrm{Fe}}/N_{\mathrm{H}}) + 12 = 5.50 \pm 0.01$ (five stars; Gratton et al. 2001) and $\log \varepsilon(\mathrm{Fe}) = 5.23 \pm 0.01$

Figure 1: The nearby metal-poor globular cluster NGC 6397 as seen by the Wide-Field Imager on the ESO/MPI 2.2-m. Its distance modulus is $(m - M) \approx 12.4^{m}$.

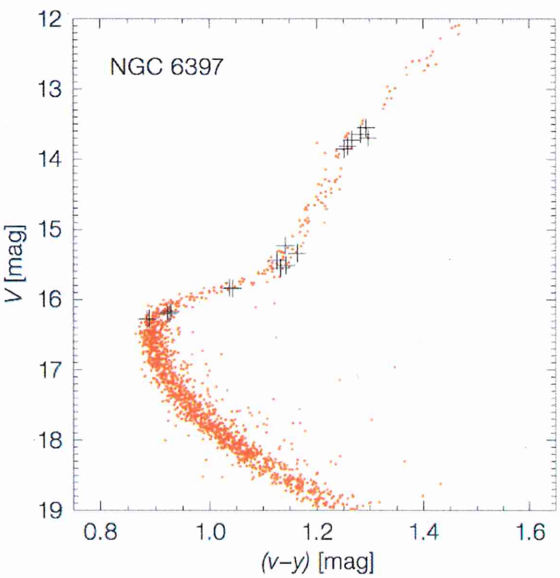


Figure 2: Colour-magnitude diagram of NGC 6397 with the FLAMES-UVES targets marked by the crosses. According to literature values, the metallicity of this cluster is just below 1/100th solar ([Fe/H] ≈ −2.1). The data were acquired with the Danish 1.54-m telescope on La Silla.

(seven stars, assuming LTE, Thévenin et al. 2001), where the error given is the standard deviation of the mean. Obviously, these results are quite incompatible with one another. Gratton et al. backed up their high metallicity scale by analysing three stars at the base of the red-giant branch (RGB) which gave $\log \varepsilon(Fe)_{LTE} = 5.47 \pm 0.03$ suggesting the good agreement between the two groups of stars to be "a constraint on the impact of diffusion". But what if Thévenin et al. were right with their turnoff-star metallicity?

We started to investigate this issue in mid-2003 and uncovered potential systematic effects in the temperature determination of the Gratton et al. analysis which could produce the apparent abundance differences between the two analyses and mimic the good agreement between the turnoff and base-RGB stars. The problems found concern the imperfect removal of blaze residuals in the UVES pipeline spectra that Gratton et al. used to set constraints on the effective temperatures of the stars from the Balmer line Hα (cf. Korn 2002). With the help of sophisticated echelle-data reduction routines developed by Nikolai Piskunov and Jeff Valenti, we could show that the systematic corrections are non-negligible amounting to −250 K. We subsequently applied for observing time with FLAMES-UVES to investigate this issue further. Fibre-fed spectrographs are less prone to the above-mentioned problems and this multi-object facility seemed ideally suited for this research.

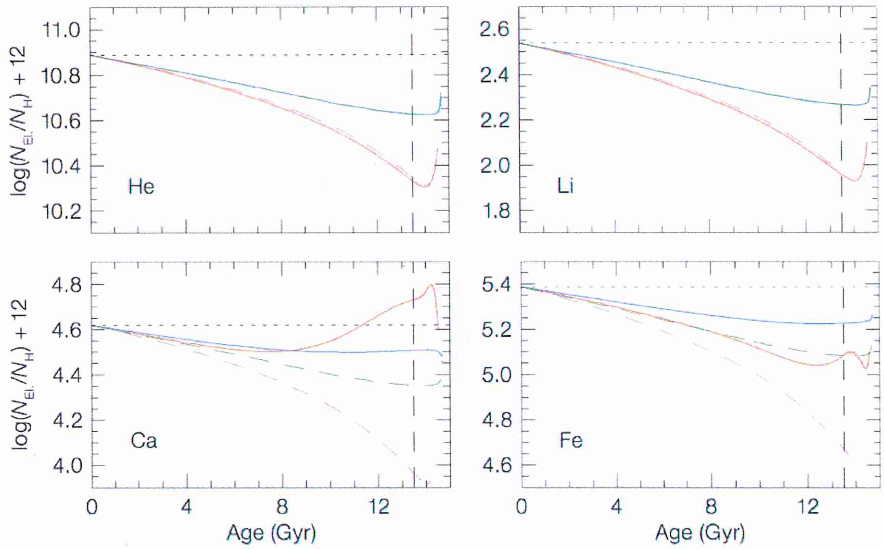
The proposal was accepted, but was moved to Visitor Mode, as we had requested the 'old' (now 'B') high-resolution settings for GIRAFFE. The visit to Paranal in June of 2004 was fruitless: high winds and thick clouds did not allow us to collect more than 20 % of the necessary data. We continued the analysis of the archival data and in a talk at the ESO-Arcetri workshop on "Chemical Abundances and Mixing in Stars" in September 2004 concluded that "gravitational settling of iron of up to 0.1 dex at [Fe/H] ≈ −2 seems possible".

A second chance with FLAMES

The successful reapplication for observing time in Period 75 gave us a second chance, this time in Service Mode. We observed a variety of stars in NGC 6397, from the turnoff to the red-giant branch. In every observing block, two UVES fibres were given to two stars in the middle of the subgiant branch (SGB), one fibre monitored the sky background. Five turnoff stars were observed for a total of 12 hours, while the six RGB stars only required 1.5 h to reach a S/N of 100. With a total integration time of 18 h, the two SGB stars have the highest S/N. The 130 fibres to GIRAFFE were filled with stars along the SGB. After receiving the data, the analysis could begin, first with a look to the effective temperatures of the turnoff stars. Already at this early stage, we learned that our preliminary analysis essentially pointed in the right direction.

The fully spectroscopic analysis of the 18 FLAMES-UVES targets took a few months. Meaningful results were only obtained once we had properly accounted for the sky background (via the sky fibre) and the fibre-to-fibre throughput correction. By November 2005 the spectroscopic results were ready and we asked Olivier Richard to compute diffusion models including radiative accelerations and turbulent mixing for comparison with our derived abundances. It is mainly

Figure 3: Theoretical predictions for a 0.77 $M_\odot$, [Fe/H] = −2 star (located at the turnoff after 13.5 Gyr) as a function of age using different input physics: with atomic diffusion only (dashed magenta), with atomic diffusion and radiative levitation (red), with atomic diffusion and turbulent mixing, but without radiative levitation (dashed green), with atomic diffusion, turbulent mixing and radiative levitation (blue). The dashed horizontal line indicates the original abundance. The panels for Ca and Fe clearly show the importance of radiative levitation for heavy elements. The blue model describes our observations of calcium and iron best.



the overall size of metal diffusion (in terms of iron) and the behaviour of calcium which set limits on the unknown strength of turbulent mixing (see Figure 3). The analysis is based on traditional 1D models (see above), but for iron and calcium detailed (non-LTE) line formation was used. We also investigated the impact of using hydrodynamic model atmospheres and found very similar results for weak lines.

The main challenge lies in determining a realistic effective-temperature *difference* between the turnoff and the RGB stars. This is because most spectral lines originate from neutral species which react most strongly to the temperature. Besides, the surface-gravity difference is well constrained by the apparent-magnitude difference of stars at a given distance.

For the spectroscopic analysis, we rely on Hα which gives an effective-temperature difference between turnoff and RGB stars of 1124 K (see Table 1). This number is in excellent agreement with the photometric estimate based on the Strömgren index (*v*–*y*) which indicates 1108 K. The surface-gravity differences agree equally well, the (logarithmic) spectroscopic value being 0.05 dex smaller than the photometric one. This good agreement between two independent techniques gave us confidence that we could determine relative abundance *differences* with high accuracy.

The diffusion signature

We uncovered systematic trends of abundances with evolutionary phase. The best determined abundance is that of iron for which the analysis rests on 20–40 lines of Fe I and Fe II. The abundance difference between turnoff and RGB stars is found to be (0.16 ± 0.05) dex which is significant at the 3σ level. Other elements were also investigated (calcium and titanium). The trends for these elements are found to be shallower than for iron which is a specific prediction of the diffusion model with turbulent mixing (see Figures 4 and 5).

This is the first time that metal diffusion in old stars is constrained by means of observations. Via the diffusion model,

Table 1: Mean stellar parameters of the FLAMES-UVES stars. Typical errors on T_{eff} and log *g* are 150 K and 0.15, respectively. The errors in log ε(Fe) are the combined values of the line-to-line scatter of Fe I and Fe II for the individual stars propagated into the mean value for the group.

Stars	#	T_{eff} [K]	log (*g* [cm/s])	log ε(Fe)
Turnoff	5	6254	3.89	5.23 ± 0.04
Subgiant	2	5805	3.58	5.27 ± 0.05
base-RGB	5	5456	3.37	5.33 ± 0.03
RGB	6	5130	2.56	5.39 ± 0.02

Figure 4: Abundance variations for a 0.77 $M_\odot$, [Fe/H] = −2 star after 13.5 Gyr. As in Figure 3, the model describing our observations is the blue one. Among the heavy elements (Z ≥ 20), the abundance change is minimal for calcium and titanium, while it is largest for iron and nickel. Lighter elements show even larger variations (e.g. magnesium and aluminium), but are subject to anticorrelations in globular clusters (Gratton et al. 2001). Of all elements, helium and lithium are affected the most.

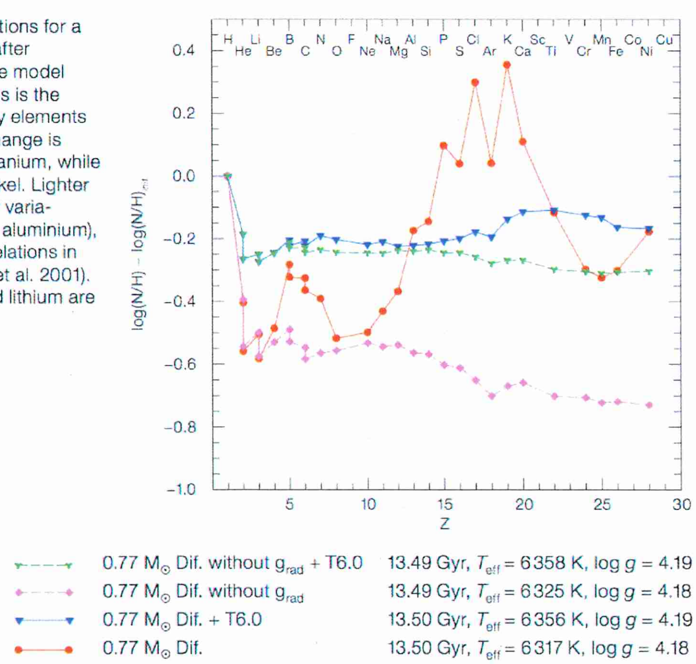
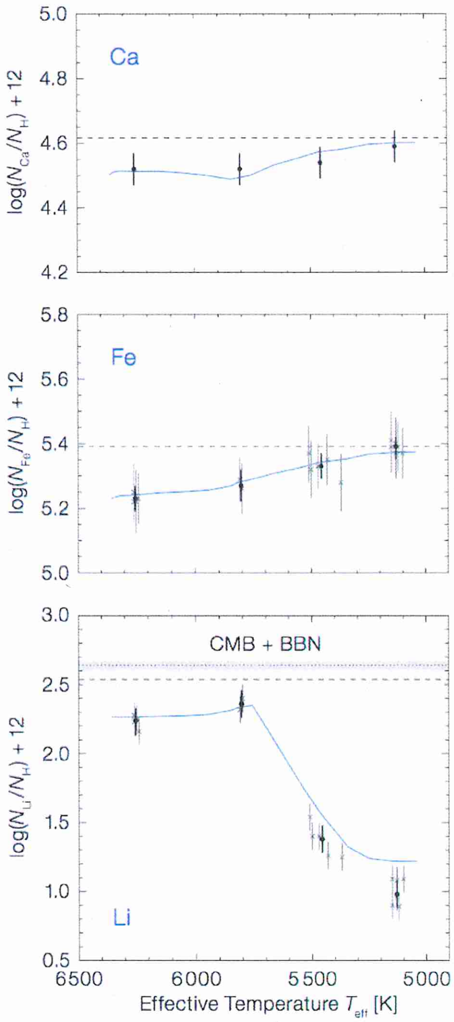


Figure 5: Observed trends of abundance with effective temperature for calcium, iron and lithium. The blue line represents the prediction from the diffusion model with turbulent mixing at an age of 13.5 Gyr (see Figure 3) with the dashed line indicating the original abundance. Measurements for individual stars are marked by crosses, group averages by bullets. For calcium, measurements were made on the group-averaged spectra to increase the S/N.



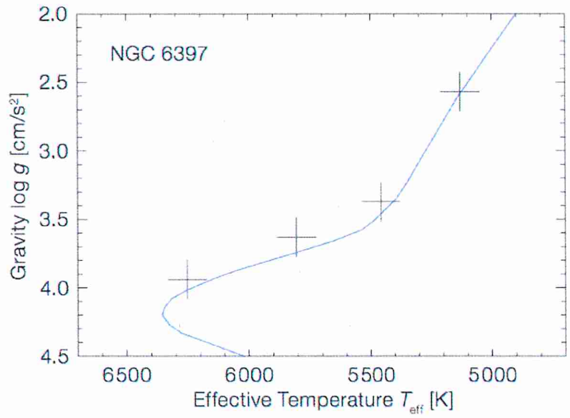


Figure 6: Kiel diagram showing the mean positions of the stars relative to a 13.5 Gyr isochrone constructed from the diffusion model with turbulent mixing. Unlike in Table 1, helium diffusion has been considered as a structural effect in the spectroscopic analysis which results in higher gravities (by +0.05 dex) for the turnoff and SGB stars (see Korn et al. 2006 for details).

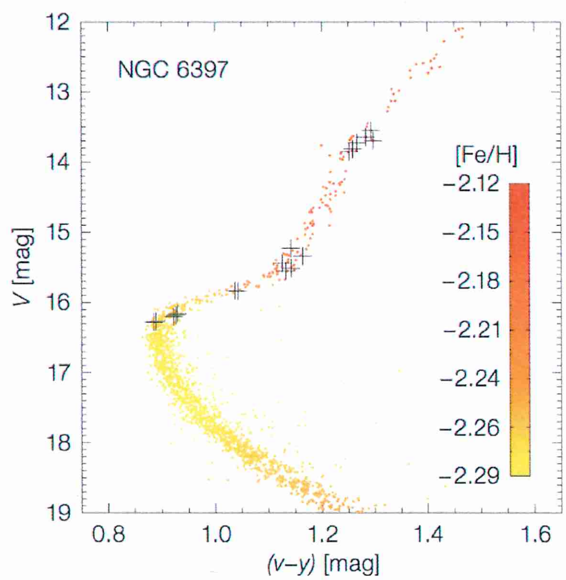


Figure 7: Colour-magnitude diagram of NGC 6397 with the FLAMES-UVES targets marked by the crosses. The colour-coding represents abundance trends in iron taken from the diffusion model with turbulent mixing calibrated on the measured abundance trends. All stars were once born with an initial iron abundance around [Fe/H] = −2.12, but unevolved stars now display lower abundances in their atmospheres.

this also constrains helium diffusion. Comparison with a 13.5 Gyr isochrone constructed from the diffusion model with turbulent mixing shows that the spectroscopic stellar parameters meet the cosmological age constraint (see Figure 6). Residual discrepancies are small, but may point towards a somewhat younger age for NGC 6397. As can be seen in Figure 3, the absolute age assumed has only a minor impact on the results.

While helium diffusion is nowadays considered a standard ingredient in stellar-evolution theory, this is not the case for metal diffusion. The latter has, however, a smaller impact on stellar evolution of metal-poor stars and we therefore expect only moderate changes to isochrone ages of globular clusters in general (nonetheless, globular clusters are now more intriguing objects than ever, see Figure 7). When it comes to unevolved field stars, the situation is different: the high ages for halo field stars that are reported in the literature are systematically overestimated by underestimated metallicities. Together with helium diffusion, the removal of this bias will likely bring down field-star isochrone ages by several billion years.

The diffusion of lithium and its cosmological implications

The recent upward revision of the baryonic matter content (Ω_b) of the Universe by experiments like WMAP (see Spergel et al. 2006 for the most recent results) has led to revised abundances of deuterium, helium and lithium produced in Big-Bang nucleosynthesis (BBN). More lithium than previously thought is found to be produced in BBN (log ε(Li)$_{BBN}$ = 2.64 ± 0.03, "CMB + BBN" in Figure 5). This has led to a distressing difference of about a factor of two or more with respect to the common abundance measured in stars on the Spite plateau. We now find that, once atomic diffusion is accounted for, the stellar abundances (log ε(Li) = 2.54 ± 0.10) are in good agreement with the primordial lithium abundance (Figure 5). Note that we even seem to see the effects of atomic diffusion in the behaviour of lithium in the turnoff and SGB stars: the measured upturn towards the SGB stars (before dilution sets in) is a specific prediction of the diffusion model.

With this work, the existence of the Spite plateau is more fascinating than ever: it is essentially of cosmological origin, but is *uniformly* lowered by physical processes in the stars. This theoretical idea has been around for decades, yet it never really caught on with the observers. Only recently, with the latest diffusion models making such a uniform lowering plausible and the WMAP results constraining the primordial lithium abundance, has the idea gained credence. Atomic diffusion may thus resolve the cosmological lithium discrepancy (Korn et al. 2006), but we caution that other effects (the absolute temperature scale of Population II stars and the related issue of a trend of lithium with metallicity, the chemical evolution of lithium in the early Galaxy, see Asplund et al. 2006 for a recent review) may also play a significant role.

This work highlights three methodological points: the possibilities of the new generation of multi-object spectrometers at the largest telescopes, the virtue of a homogeneous and consistent analysis of all relevant criteria (spectroscopic as well as photometric) and the benefits of developing physical models to a higher degree of self-consistency. The empirical result that atomic diffusion affects atmospheric chemical abundances of old unevolved stars and that models can account for its effects is significant and has a number of consequences, some of which were discussed above. For the time being, turbulent mixing is introduced in an ad-hoc manner, without specifying the physics behind it. Likewise, we neglect the spectral effects of the thermal inhomogeneities and the 3D nature of convection in our traditional 1D analysis. Thus, a lot remains to be done before the quality of current observational data is adequately matched by physical models of stars, so that we can fully read the fingerprints of chemical elements in stellar spectra.

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VLT Image of Globular Cluster 47 Tuc

47 Tucanae is an impressive globular cluster that is visible with the unaided eye from the southern hemisphere. It appears as big on the sky as the full moon.

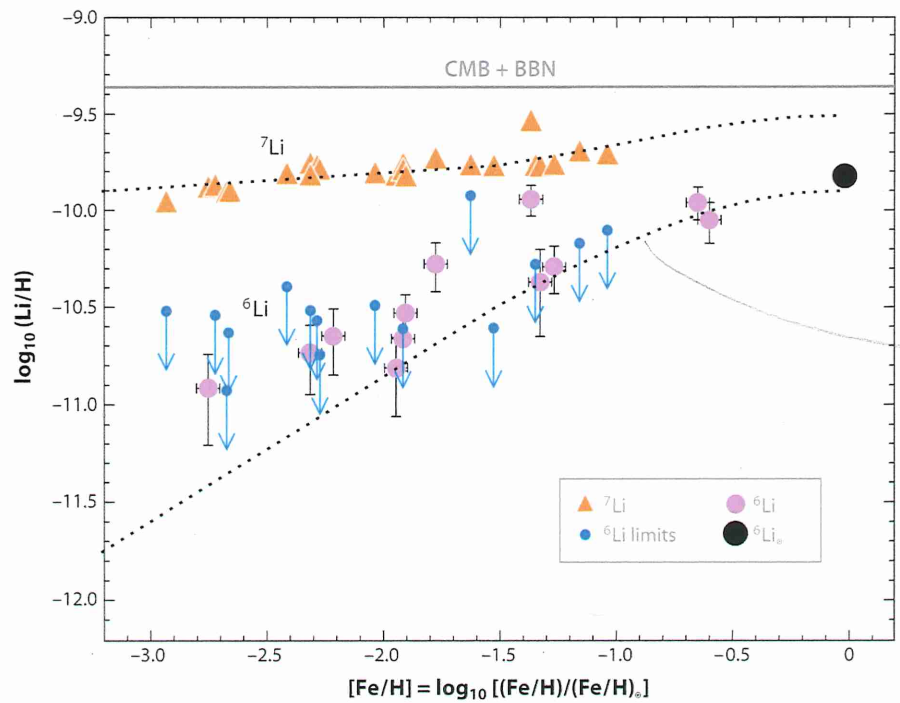
The colour image of 47 Tucanae presented here was taken with FORS1 on ESO's Very Large Telescope in 2001. The image covers only the densest, very central part of the cluster. The red giants, stars that have used up all the hydrogen in their core and have increased in size, are especially easy to pick out.

47 Tuc is so dense that stars are less than a tenth of a light year apart, which is about the size of the Solar System. By comparison, the closest star to our Sun, Proxima Centauri, is four light years away. This high density can cause interactions; these dynamic processes are the origin of many exotic objects, to be found in the cluster.

Thus, 47 Tuc contains at least twenty millisecond pulsars (neutron stars). The Hubble Space Telescope recently also looked at 47 Tuc to study planets orbiting very close to their parent stars. These observations showed that such 'hot Jupiters' must be much less common in 47 Tucanae than around stars in the Sun's neighbourhood. This may tell us either that the dense cluster environment is unhealthy for even such close planets, or that planet formation is a different matter today than it was very early in our Galaxy's history.

(Based on ESO Press Photo 20/06)

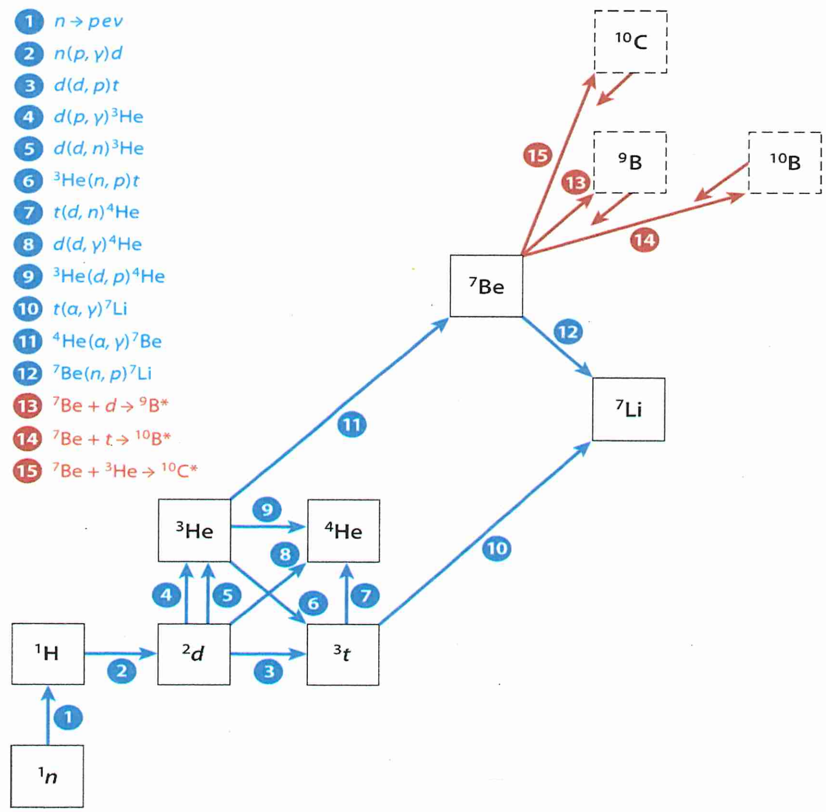
ESO PR Photo 20/06 is based on data obtained with FORS1 on Kueyen, UT2 of the Very Large Telescope. The image, seven arcmin wide, covers the central core of the 30 arcmin large globular cluster. The observations were taken in three different filters: *U*, *R*, and a narrow-band filter centred around 485 nm, for a total exposure time of less than five minutes. The data were extracted from the ESO Science Archive and processed by Rubina Kotak (ESO) and the final image processing was done by Henri Boffin (ESO). North is up and East is to the left.



^{6}Li from ^{9}Be and CR spallation ratio

assumes ^{6}Li not depleted in stars

Fields BD. 2011.
Annu Rev. Nucl. Part. Sci. 61:47–68



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Annu Rev. Nucl. Part. Sci. 61:47–68

Annual Reviews

STELLAR SPECTROSCOPY

- NON-LTE
- GRANULATION + NON-LTE
- ^6Li ?

NUCLEAR PHYSICS

- $^3He(\alpha,\gamma)^7Be$ fixed by solar ν's
- MISSED RESONANCES? RATES OTHERWISE WELL MEASURED
  $^7Be + d \Rightarrow {}^9B^*$ (16.71 MeV) ?
  + others - now studied ?

SEEKING TO DESTROY ^7Be FASTER

NON-STD BB SYNTHESIS?

- PARTICLE PHYSICS ?
- COSMOLOGY ?

→ ONE EXAMPLE

DARK MATTER PARTICLES

- decaying (quickly or) after a few minutes interact with BB products
- decays generally produce SM particles

  - $N + {}^{4}He \rightarrow \begin{cases} 2n + 2p + N \\ d + d + N \\ d + {}^{[illegible]}A \end{cases}$

and

$$n + {}^{7}Be \rightarrow p + {}^{7}Li$$

for $\tau(N)$ v. short, ^{7}Li rel to ^{7}Be decayed faster (lower Coul. B)

and

$$d + {}^{4}He \rightarrow {}^{6}Li + \gamma \quad !$$

THE LITHIUM PROBLEM

- FIELDS (Ann. Rev. Nuc. Part Sci, 61, 47, 2011)
  - STELLAR SPECTROSCOPY /ATMOSPHERES
  - STELLAR ASTROPHYSICS
  - NUCLEAR PHYSICS
  - THE BIG BANG
    - COSMOLOGICAL MODEL
    - PARTICLE PHYSICS

see Pospelov + Pradler AR Nuc. Part. Sci 60 539 2010