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Beryllium enhancement as evidence for accretion in a lithium-rich F dwarf

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ABSTRACT

The early F dwarf star ‘J37’ in the open cluster NGC 6633 shows an unusual pattern of photospheric abundances, including an order-of-magnitude enhancement of lithium and iron-peak elements, but an under-abundance of carbon. As a consequence of its thin convection zone these anomalies have been attributed to either radiative diffusion or the accretion of hydrogen-depleted material. By comparing high-resolution Very Large Telescope/UV–Visual Echelle Spectrograph spectra of J37 (and other F stars in NGC 6633) with syntheses of the Be II doublet region at 3131 Å, we establish that J37 also has a Be abundance [$A(\mathrm{Be}) = 3.0 \pm 0.5$] that is at least 10 times the cosmic value. This contradicts radiative diffusion models that produce a Li over-abundance, as they also predict photospheric Be depletion. Instead, since Be is a highly refractory element, it supports the notion that J37 is the first clear example of a star that has accreted volatile-depleted material with a composition similar to chondritic meteorites, although some diffusion may be necessary to explain the low C and O abundances.

Key words: accretion, accretion discs – diffusion – stars: abundances – stars: atmospheres – stars: chemically peculiar – stars: evolution.

1 INTRODUCTION

The star J37 [= TYC 445- 1972-1, GSC 00445−01972] is a remarkable early F-type dwarf member of the Hyades-age open cluster NGC 6633 (Jeffries 1997). It demonstrates several chemical peculiarities, including factors of ≃5–10 enhancement in Fe, Ni and Li and an under-abundance of carbon (Deliyannis, Steinhauer & Jeffries 2002, hereafter DSJ02; Laws & Gonzalez 2003, hereafter LG03).

DSJ02 suggested that radiatively driven diffusion, specifically the models of Richer & Michaud (1993), produce a ‘Li-peak’ over a narrow range of effective temperatures ($6900 < T_{\mathrm{eff}} < 7100$ K at 800 Myr), caused by the very thin surface convection zone (SCZ) of J37 reaching down to a radiatively supported reservoir of Li atoms. This hypothesis explains some (but not all) of the other abundance anomalies, but is contradicted by recent ‘turbulent’ diffusion models (e.g. Richer, Michaud & Turcotte 2000) where instead a modest under-abundance of Li is predicted.

Alternatively, LG03 suggested that accretion of material depleted of elements with low condensation temperatures into the thin SCZ can explain the high abundances of more refractory elements like Li and Fe, whilst simultaneously resulting in little enrichment of volatiles like C and O. A problem here is that C and O may be under-abundant in J37, perhaps indicating a later role for diffusion processes similar to those in Am stars.

The Be abundance of J37 would provide an interesting test of these competing hypotheses. Be is the next lightest metal after Li, but may behave quite differently in diffusion models because of its differing electronic structure. The Richer & Michaud (1993) diffusion models predict that at the age and T_{eff} of J37, an over-abundance of Li should be accompanied by an absence of photospheric Be. In contrast, because Be has a very high condensation temperature, the accretion of volatile-depleted material would lead to a Be enhancement as high as or even a little higher than that for Li and Fe.

This Letter presents an analysis of high-resolution, high signal-to-noise ratio spectra of J37 and three comparison stars in NGC 6633. We derive Be abundances by comparing the spectra with a model synthesis in the region of the Be II doublet at 3130.4 and 3131.1 Å. We also (re)determine the abundances of several other elements and compare these with the predictions of diffusion and accretion models.

2 OBSERVATIONS

High-resolution spectra of the NGC 6633 stars J1, J3, J16 and J37 (see Jeffries 1997) were obtained with the UV–Visual Echelle Spectrograph (UVES) mounted on the UT2 8.2-m European Southern Observatory (ESO) Very Large Telescope (VLT) between 2003

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Table 1. Stellar parameters for J1, J3, J16 and J37.

Star	T_{eff} (K)	log g (cm s^{-2})	ξ (km s^{-1})	v sin i (km s^{-1})
J1	6870 ± 80	4.05 ± 0.15	2.29 ± 0.12	19.0 ± 0.9
J3	6310 ± 60	4.00 ± 0.20	1.53 ± 0.11	10.8 ± 0.6
J16	6320 ± 60	4.25 ± 0.15	1.27 ± 0.10	7.2 ± 0.4
J37	7580 ± 80	4.05 ± 0.15	3.33 ± 0.14	29.4 ± 1.2

June 13 and July 6. The standard DIC1/346/580 configuration with a 1.2-arcsec slit was used to take four exposures of between 900 and 1500 s for each star. The wavelength range 3050–6820 Å (orders 152-90) was covered at a resolving power of 35 000. The final signal-to-noise ratio, achieved after co-adding the exposures, was 50–70 per 0.03-Å pixel in the Be II region (at 3131 Å), but much higher (200–300) at redder wavelengths.

3 ANALYSIS

3.1 Atmospheric parameters

Our analysis used the Kurucz ATLAS9 model atmosphere grids with no convective overshoot (Kurucz 1993; Sbordone et al. 2004). Target spectra were examined for suitably unblended Fe I and Fe II lines (in the red part of the spectra). The equivalent widths (EWs) of these were measured in the targets and also in the solar spectrum using the National Optical Astronomy Observatory (NOAO) Solar Atlas (Kurucz et al. 1984). Oscillator strengths were set assuming the solar parameters $T_{\mathrm{eff}} = 5777$ K, log $g = 4.44$, microturbulence $\xi = 1.25$ km s^{-1}, average metallicity [M/H] = 0.0 and absolute Fe abundance $A(\mathrm{Fe}) = 12 + \log\ [N(\mathrm{Fe})/N(\mathrm{H})] = 7.54$. Differential Fe abundances were determined from these lines in the NGC 6633 stars along a locus of T_{eff} and log g values that gave equal mean abundances from the Fe I and Fe II lines. Microturbulence values were estimated by requiring no trend in abundance from the Fe I lines with EW.

The final atmospheric parameters were settled on by estimating T_{eff} from a mean of the values given by (i) relationships between $V - I$ and $V - K$ colour indices and T_{eff} (Alonso, Arribas & Martínez-Rodger 1996), and (ii) the combination of *VIJHK* photometry and a semi-empirical infrared flux method using the ATLAS9 models. The *VI* photometry came from Jeffries (1997); *JHK* photometry came from the Two Micron All-Sky Survey (2MASS) (Cutri et al. 2003). An average atmospheric metallicity, [M/H], of 0.0 was assumed for J1, J3 and J16, whilst [M/H] = +0.5 was assumed for J37. In principle we could have iterated these values in the light of our final abundance estimates, but the reason we chose to use the $V - I$ and $V - K$ colours is that they are almost insensitive to metallicity variations in any case. Extinction and reddening were accounted for using $E(B - V) = 0.165$ from Jeffries et al. (2002) and the reddening law of Rieke & Lebofsky (1985). Defining T_{eff} leads to a log g from the ionization balance locus.

Uncertainties in T_{eff} were calculated from the standard error in the mean of the three estimation methods. These consequently lead through to additional uncertainties in log g, microturbulence and abundances. The final atmospheric parameters and an estimate of v sin i for each star obtained by fitting several of the unblended Fe lines are given in Table 1. [Fe/H] values are given in Table 2.

3.2 Blending elements

The Be II doublet region contains many atomic lines. Because of finite resolution and rotational broadening, estimates are required for the abundances of elements that contribute significantly to absorption in this region – namely, Ti, V, Mn and Co. We also included Ca in our analysis, which is important for distinguishing between accretion and diffusion scenarios and for which only one and two lines were analysed by DSJ02 and LG03 respectively. The EWs of unblended lines in the red region of the spectra were measured for these elements, converted into abundances using the atmospheric parameters described in Section 3.1 and averaged. The results are given in Table 2 along with the number of lines used for each element. These abundances are differential with respect to the Sun, because the same procedure for adjusting the oscillator strengths was performed. No unblended lines were available for V and Co in J37. Here, the assumption was made that [V/H] and [Co/H] were equal to [Fe/H]. We confirmed that assuming a mean cluster abundance for these elements in J37 would have made little difference to our final derived Be abundance. Errors in the Ca, Ti and Fe abundances are dominated by T_{eff} uncertainties. For Mn, V and Co, the scatter in the estimates for individual lines is equally important.

The Be II region also contains OH and CO molecular lines. The C abundance was measured in the same manner as above for J1, J3 and J16 and from a synthesis of the C lines at 5380 and 6587 Å for J37, using an updated version of the local thermodynamic equilibrium (LTE) MOOG analysis code (Sneden 2002). The abundance of O in J1 and J37 was estimated using the 7771–7775 Å O I triplet EW measurements of LG03, but using our atmospheric parameters and assuming $A(\mathrm{O}) = 8.94$. The quoted differential O abundances contain non-LTE corrections of −0.51 for J1 and −0.62 for J37, interpolated from tables in Takeda (1997).

3.3 Be and Li abundances

LTE Be and Li abundances were determined via spectrum synthesis using MOOG and atmospheres interpolated from the ATLAS9

Table 2. Elemental abundances in J1, J3, J16 and J37. The number of lines/features used in the analyses are indicated in brackets.

X	$[\mathrm{X/H}]_{\mathrm{J1}}$	n	$[\mathrm{X/H}]_{\mathrm{J3}}$	n	$[\mathrm{X/H}]_{\mathrm{J16}}$	n	$[\mathrm{X/H}]_{\mathrm{J37}}$	n
C	−0.15 ± 0.03	(7)	−0.14 ± 0.03	(4)	−0.11 ± 0.11	(5)	−0.50 ± 0.15	(2)
O^{a}	+0.14 ± 0.05	(3)					−0.08 ± 0.15	(3)
Ca	−0.07 ± 0.05	(14)	−0.06 ± 0.02	(16)	−0.04 ± 0.03	(16)	+0.66 ± 0.04	(10)
Ti	−0.15 ± 0.04	(10)	−0.12 ± 0.04	(23)	−0.13 ± 0.04	(28)	+0.77 ± 0.10	(3)
V	−0.18 ± 0.04	(3)	−0.26 ± 0.05	(4)	−0.17 ± 0.05	(7)	+0.67^{b}	
Mn	−0.22 ± 0.08	(4)	−0.30 ± 0.06	(6)	−0.34 ± 0.05	(6)	+0.54 ± 0.11	(3)
Fe	−0.31 ± 0.04	(48)	−0.16 ± 0.03	(48)	−0.15 ± 0.03	(58)	+0.67 ± 0.04	(40)
Co	−0.10 ± 0.18	(3)	−0.17 ± 0.06	(5)	−0.33 ± 0.07	(4)	+0.67^{b}	

[a] NLTE – derived from EWs reported by LG03. [b] Assumed to scale with [Fe/H] – no unblended lines accessible in the spectrum.

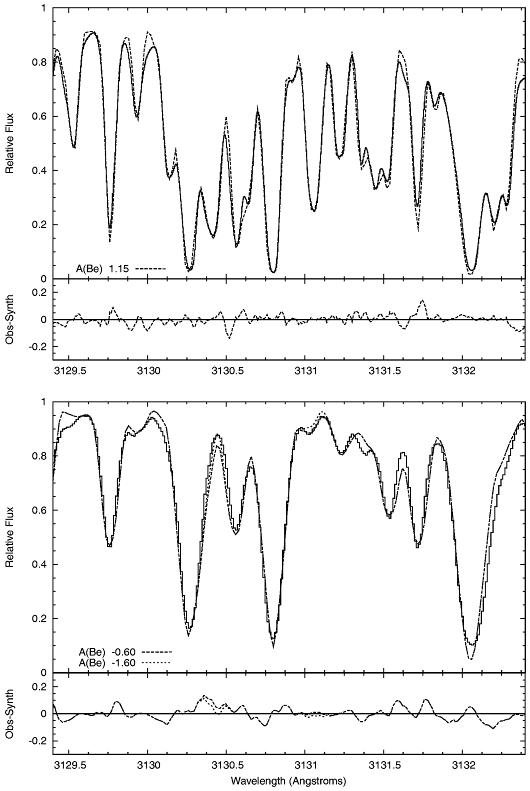

Figure 1. Syntheses of the Be II doublet (3130.4 and 3131.1 Å) region compared with the NOAO Solar Atlas (upper panel) and Procyon (lower panel). The upper portion of each plot shows the spectrum (solid line) and synthesis (dashed lines). The lower portions show the residuals.

(Kurucz 1993) grids. The well-established line list in the region of the Li I 6708-Å doublet was taken from Ford et al. (2002). Atomic and molecular identifications, wavelengths, excitation potentials and log *gf*-values used for the Be II region were taken from King, Deliyannis & Boesgaard (1997), supplemented by molecular lines from the Kurucz CD-ROMs. Oscillator strengths were tuned to better fit both the NOAO Solar Atlas *and* a spectrum of Procyon (F5 IV) obtained with UVES by Bagnulo et al. (2003) (see Fig. 1).

We have largely adopted the corrections discussed in King et al. (1997) and also the philosophy that log *gf*-values needing the least adjustment were varied where a number of lines affected the same feature. The resulting solar $A(\mathrm{Be}) = 1.15$, agreeing with previous photospheric determinations (Anders & Grevesse 1989), whilst Procyon is confirmed as very Be-depleted, $A(\mathrm{Be}) < -0.6$. To match the Procyon spectrum (with assumed $T_{\mathrm{eff}} = 6700$ K, $\log\ g = 4.05$) and the Sun simultaneously, a CH line at 3131.058 Å was removed, the wavelength of the Mn I line at 3131.037 Å was shifted to 3131.017 Å as suggested by King et al. (1997) and its $\log\ gf$-value was increased by 1.563 dex. This modified line list provides good fits (especially in the vicinity of the Be II lines) for all the stars in this study (see Fig. 2).

The estimated LTE Be and Li abundances are listed in Table 3. The enormous Li over-abundance of J37, compared with a meteoritic value of $A(\mathrm{Li}) = 3.3$, is confirmed. The Li abundances of J1, J3 and J16 are consistent with an initial meteoritic abundance which has undergone some depletion as a result of internal mixing of Li. The Be abundances of J1, J3 and J16 also appear depleted with respect to both solar [$A(\mathrm{Be}) = 1.15$] and meteoritic [$A(\mathrm{Be}) = 1.42$] abundances. This has been seen in other Hyades-age clusters (e.g. Boesgaard, Armengaud & King 2003), although the large ratio of Li to Be in J1 and J3 suggests either that more Be than Li has been depleted, which seems unlikely, or that the initial Li to Be ratio in NGC 6633 may be a few tenths of a dex higher than in meteorites or other young clusters. However, this uncertainty in the initial Be content of NGC 6633 is dwarfed by the massive over-abundance of Be estimated for J37, where the quoted error is dominated by fitting uncertainties rather than atmospheric parameter uncertainties.

4 DISCUSSION

This Letter improves on the work of DSJ02 and LG03 in several respects. The stellar parameter determinations are more secure thanks to (i) the use of metallicity-insensitive colour indices for the T_{eff} determination; (ii) 34–51 Fe I lines for the metallicity and microturbulence estimates; and (iii) a total of 40–58 Fe lines for the log *g* determination from the ionization balance. The determination of abundance anomalies for J37 with respect to the cluster is improved by the use of three cluster comparison stars (LG03 used only J1), the addition of Be and Mn abundances and a more reliable determination of the C and Ca abundances using more spectral features, and the fact that an apparent mistake in the application of non-LTE O-abundance corrections by LG03 has been rectified.

Assuming an initial $A(\mathrm{Be}){=}1.2 \pm 0.2$ for NGC 6633, then J37 is enhanced in Be by 1.8 ± 0.5 dex (according to our LTE analysis). Likewise, we confirm previous results that Li is enhanced by about 1.10 ± 0.25 dex [assuming an initial $A(\mathrm{Li}){=}3.3 \pm 0.2$], Fe by about 0.85 ± 0.06 dex (compared with the average [Fe/H] of the three comparison stars), Ti by 0.90 ± 0.10 dex, Mn by 0.83 ± 0.12 dex and Ca by 0.72 ± 0.04 dex. These over-abundances are larger than found by DSJ02 and LG03, because the T_{eff} that we have derived is about 500 K higher than indicated by the $B - V$ based estimate in DSJ02 and 275 K hotter than the spectroscopic estimate in LG03 (about 1 error bar). Given the abundance anomalies in the atmosphere of J37, it would not be surprising if a T_{eff} based on $B - V$, which is heavily affected by line blanketing, was inaccurate. The optical/infrared indices that we have used are much more insensitive to detailed composition.

The large Be abundance found for J37 offers no support to the diffusion hypothesis put forward by DSJ02. The only set of diffusion models that predicted a large Li enhancement also predicted that Be should be completely depleted from the photosphere (Richer & Michaud 1993). Furthermore, the new T_{eff} that we have estimated for J37 places it > 400 K hotter than the predicted position of the Li peak at the age of NGC 6633. The extreme sensitivity of diffusion predictions to details of the atmosphere and atomic physics may mean that future calculations are more successful; but currently published models fail.

The accretion hypothesis can satisfactorily explain why there are simultaneous increases of Be, Li and Fe but not of C and O. Be has a higher condensation temperature than either Fe or Li (Lodders 2003) and should be present at close to its primordial value in any volatile-depleted material that is accreted.

Taking Fe as the primary compositional tracer and making the simplifying assumptions that accreted material is mixed only within the SCZ and no diffusion or gravitational settling takes place after accretion, we can estimate the mass of accreted material that would explain the observed abundance. According to the models of Richer et al. (2000), the T_{eff} of J37 matches that for a star of 1.6 $\mathrm{M}_{\odot}$ at an age of 600 Myr and such a star would have $\log\ g = 4.15$, in excellent agreement with our spectroscopically determined value. The mass of the SCZ in such a star is of the order of 10^{-6} $\mathrm{M}_{\odot}$, and

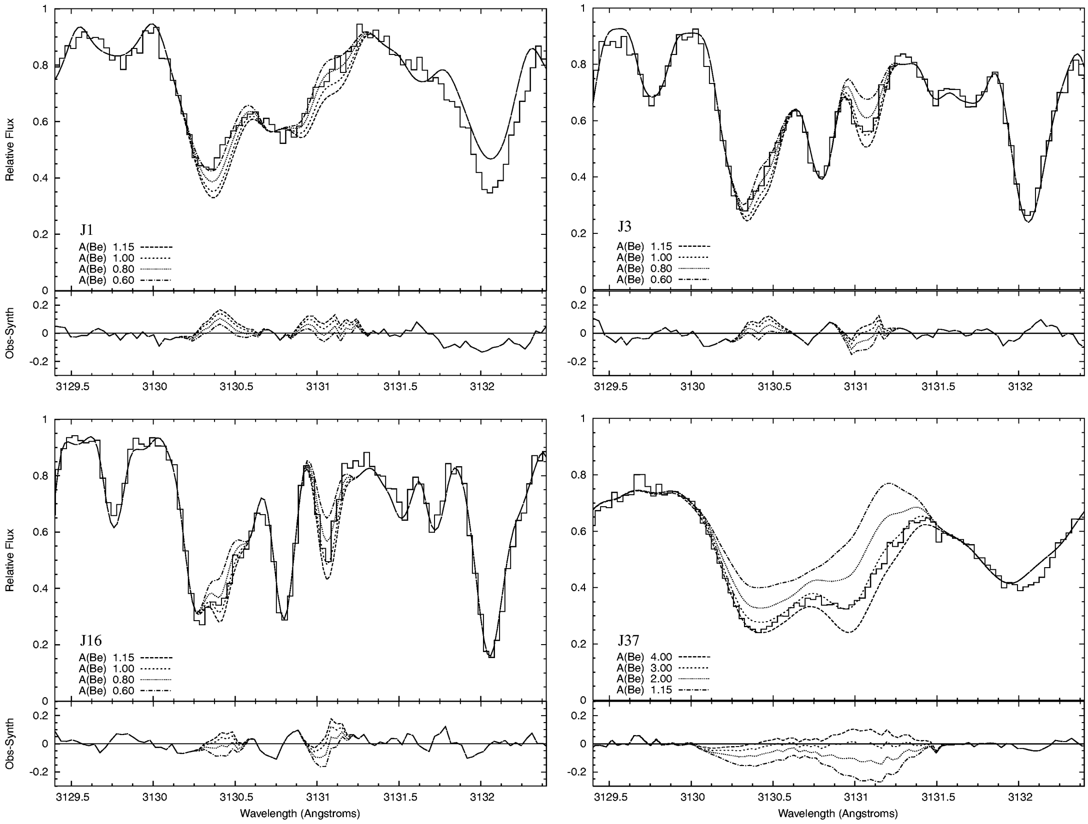

Figure 2. Spectral synthesis of the Be II doublet region in stars J1, J3, J16 and J37. In each case the upper plot shows the spectrum (stepped line) and syntheses with various Be abundances, and the lower plot shows the residuals.

Table 3. Abundances of Li and Be for J1, J3, J16 and J37.

X	$A(X)_{J1}$	$A(X)_{J3}$	$A(X)_{J16}$	$A(X)_{J37}$
Li	2.90 ± 0.11	3.10 ± 0.14	2.70 ± 0.14	4.40 ± 0.14
Be	0.70 ± 0.15	0.90 ± 0.15	0.90 ± 0.15	3.00 ± 0.50

so the quantity of (for instance) Solar system CI chondrite meteoritic material (Lodders 2003) required for the Fe enhancement observed in J37 [assuming an initial $A(\mathrm{Fe}) = 7.39 \pm 0.06$ determined from the comparison stars] would be just 0.011 $\mathrm{M}_{\oplus}$.

The accretion of this chondritic material would also result in $A(\mathrm{Li}) = 4.04$ and $A(\mathrm{Be}) = 2.13$ (assuming the initial abundances quoted earlier). In both cases the uncertainty in the initial abundance has little effect on the final abundance, and hence it appears that the measured Li/Fe and Be/Fe ratios in J37 might be too large to support the accretion hypothesis (see Table 3). Recall, however, that these abundances are calculated assuming LTE conditions. The Li I 6708-Å doublet is strongly affected by non-LTE effects at high abundances, as can be seen in Carlsson et al. (1994, see their fig. 16). They suggest an non-LTE correction to the J37 Li abundance of -0.3 dex, bringing the Li abundance in line with that predicted by meteoritic accretion. The Be abundance may also be affected by atmospheric uncertainties. Detailed non-LTE calculations at a range of T_{eff} do not yet exist, and there is also a strong suggestion (e.g. see Asplund 2004) that there is a missing source of continuum opacity at ≃3130 Å. Given that J37 is significantly hotter than the Sun and the NGC 6633 comparison stars, these two effects result in additional uncertainty in the differential Be abundances, to the extent that detailed agreement with the meteoritic accretion hypothesis should not be excluded.

Accretion of volatile-depleted meteoritic material cannot explain why the C and O abundances of J37 are *lower* than the NGC 6633 comparison stars by 0.2-0.3 dex. The accretion of 0.011 $\mathrm{M}_{\oplus}$ of chondritic material should result in $[\mathrm{C/H}] = +0.02 \pm 0.05$ and $[\mathrm{O/H}] = +0.44 \pm 0.05$ (assuming initial abundances of -0.13 and $+0.14$ respectively), about 0.5 dex higher than observed in J37. This discrepancy can only be partly resolved by accreting material that is even more depleted in volatiles (such as 'bulk Earth' material – see LG03). It seems likely, as suggested by LG03, that some diffusion *has* occurred in J37, either before or after the accretion event(s). Certainly C and O depletions of the order of 0.5 dex are feasible according to the recent models of Richer et al. (2000), and are less severe than the depletions observed in many classic Am/Fm stars. However, given that models and also observations of Am stars show simultaneous depletions of similar magnitude for the refractory element Ca, accompanied by an enhancement of the iron-peak elements, it seems unlikely that diffusion can have been very effective, because $[\mathrm{Ca/Fe}] \simeq -0.1$ for J37, rather than the more typical -1 seen in Am stars.

An area for further study would be to systematically find the frequency of Li/Be-rich F stars in open clusters, to investigate (i) how common the accretion events are and (ii) how quickly diffusive or other mixing processes can remove the abundance anomalies from the photosphere. If the frequency is low it would suggest that accretion events are rare or that the effects of diffusion rapidly dilute any accreted material. If, however, the frequency is high it would suggest that accretion is common and diffusion is slow. It should be noted that the quantities of accreted material discussed in this paper are far too small to explain the enhanced metallicity of exoplanet host stars (e.g. Santos, Israelian & Mayor 2004), which generally have *much* more massive SCZs.

5 SUMMARY

We have found that that the Li-rich early F dwarf J37 is also Be-rich, with $A(\mathrm{Be}) = 3.0 \pm 0.5$. The Be over-abundance in J37 (together with 0.7–0.9 dex enhanced abundances for Ca and iron-peak elements) completely contradicts published diffusion models hypothesized to explain the Li-rich nature of J37. Instead, the enhancement of highly refractory elements like Be, Ca and Fe, together with much lower abundances of C and O, can be explained by the accretion of about 0.01 $\mathrm{M}_{\oplus}$ of volatile-depleted material such as chondritic meteorites. However, the $\sim$0.3 dex under-abundances of C and O in J37 compared with other stars in the same cluster suggest that there may still be a limited role for diffusion to play.

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