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The Lithium Isotope Ratio in Population II Halo Dwarfs: A Proposed Test of the Late Decaying Massive Particle Nucleosynthesis Scenario

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ABSTRACT

It is shown that observations of the Lithium isotope ratio in high surface temperature Population II stars may be critical to cosmological nucleosynthesis models. In particular, decaying particle scenarios as derived in some supersymmetric models may stand or fall with such observations.

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I. Introduction

The standard model of Big Bang Nucleosynthesis (c. f. Yang, et al. 1984, and references therein) has been remarkably successful in explaining light element abundances. However, in view of the significance of this model and the far reaching magnitude of its implications (e. g. low baryon density, number of neutrino species, etc.), it is important to continually look for loopholes in the arguments. One such loophole has recently been proposed by Dimopoulos, et al. (1987). They argue that certain classes of supersymmetry theories predict massive ($\geq$ GeV) particles which would be produced in the early universe and decay after the epoch of traditional Big Bang Nucleosynthesis. Dimopoulos, et al., show that such decaying massive particles might have been responsible for primordial light element abundances via hadronic showers formed when the relic particles decayed at the KeV era, thus significantly altering the standard scenario. For example, their scenario allows a baryonic density $0.03 \leq \Omega_B \leq 1.1$. They also note that it produces an initial $\frac{^7Li}{^6Li} \equiv r_{7,6}$ isotopic abundance ratio of order .1, whereas current observed values of $r_{7,6}$ range from 1.7 to 40 (Steigman and Boessgard 1986). In this note we will show that their prediction for $r_{7,6}$ should produce observable consequences. Dimoupoulos, et al. claim that given the ~ 100 ratio of the reaction rates of ^6Li to ^7Li for protonic destruction, it is possible, with sufficient astration factors, to reduce this primordial ^6Li abundance to currently observed values. However, if we accept the interpretation that the roughly flat portion of the Lithium abundance versus T_{eff} curve (Figure 1) for low metallicity halo dwarfs (Population II stars) represents the primordial lithium abundance as advocated by Spite and Spite (1982), then it is possible to predict the $r_{7,6}$ vs. T_{eff} curve for these stars. As we will show, the resulting predictions are within the limits of previous observations, but our results also show that there are a few observed stars for which a firm upper bound on $r_{7,6}$ of 1.45 is predicted. This is well below the ratio measured in any previous observations of the halo dwarfs (Maurice, Spite, and Spite 1984). Thus, a measurement of $r_{7,6} > 1.45$ for any of these stars (or any other very low metallicity halo dwarf with $\log(T_{eff}) \geq 3.8$) would not be reconcileable with the late decaying particle scenario. Further, a value $r_{7,6} \leq 1.45$ would be incompatible with "standard" Big Bang Nucleosynthesis which predicts no primordial ^6Li. The result of such observations would be of great interest since this may be the only way to produce a significant primordial ^6Li abundance.

II. Lithium Depletion in $\sim 1M_\odot$ Stars

In 1982, Spite and Spite reported their observation of the now familiar lithium abundance versus T_{eff} ($T_{eff} \propto$ mass) curve for very unevolved (low metallicity) halo dwarfs (Figure 1). This work has since been expanded and confirmed by other groups (Beckman, Rebolo, and Molaro 1987; Hobbs and Duncan 1987). The qualitative reasons for this shape are well understood. In relatively low mass, $\sim 1M_\odot$, stars the observed amounts of any element are determined by the thermonuclear burning occuring at the base of the convective envelope of the star. For decreasingly massive stars, the depth of the convective zone increases, mixing material down to correspondingly higher temperatures, resulting in greater destruction of Lithium (see e. g. Clayton 1983, pp. 472-5). It was initially assumed (Spite and Spite 1982) that the observed lithium depletion curve was due to main sequence behavior. D'Antona and Mazzitelli (1984) showed that this behavior was not possible with current models of stellar structure for very low metallicity (Z = .001) stars above $.6M_\odot$, since convective envelopes are much shallower in lower metallicity stars. Rather, they argued, lithium burning occured in the late pre-main sequence stages of star formation, after a convective envelope had formed; thus, the behavior is still seen as arising from the same qualitative effects as discussed above. With the additional assumption of extra mixing of unspecified mechanism (possibly convective overshoot, turbulence, etc.) to .7 pressure scale hights (H_p) below the convective zone, they could very closely fit not only the observed halo Lithium abundances, but also observations for low mass stars in a wide variety of evolutionary stages. Their argument is really independant of the detailed mechanism.

The reaction rates for $^6Li(p,\alpha)^3He$ and $^7Li(p,^3He)^4He$ are plotted versus temperature in figure 2. The extreme temperature dependance is responsible for the sharp rollover of the curve in figure 1. Significant burning only occurs when temperatures are reached above $\sim 2 \times 10^6$ °K for ^7Li and $\sim 1.65 \times 10^6$ °K for ^6Li. From figure 3 it is evident that even though there is a very strong dependance of the individual rates on T, their ratio, $\beta = \frac{<\sigma_6 v>}{<\sigma_7 v>}$, is relatively constant, and above threshold levels is less than 76. We can work out the single temperature relationship between the time evolution of $r_{7,6}$ and N_7 (the lithium-7 abundance).

$$r_{7,6}(t,T) = [\frac{N_7(t,T)}{N_6(t,T)}] \tag{1}$$

$$\frac{d\ N_7(t,T)}{dt} = -\rho N_7(t,T) < \sigma_7 v > \tag{2}$$

$$\frac{d\ N_6(t,T)}{dt} = -\rho N_6(t,T) < \sigma_6 v > \tag{3}$$

Where ρ is the density of the burning layer. A little algebra and differentiation yeilds:

$$\frac{-d\ ln(r_{7,6})}{dt} = \frac{d\ ln(N_7)}{dt}(\beta - 1) \tag{4}$$

Integrating and solving we get:

$$[\frac{r_{7,6}(t,T)}{r_{7,6}(0,T)}]^{-1} = [\frac{N_7(t,T)}{N_7(0,T)}]^{\beta-1} \tag{5}$$

This relates $r_{7,6}$ and N_7 at each point in the outer layer of the star, but to get the observed surface abundances we must continually average over the entire mixed region (from m_1 to m_2) (Bodenheimer 1965). Dependance on T now becomes a dependance on mass point (mass within a shell of given radius). Thus:

$$[\frac{r_{7,6\ observed}}{r_{7,6}(t=0)}]^{-1} = \frac{1}{(\Delta m)}\int_{m_1}^{m_2}(\frac{N_7(m)}{N_7(0)})^{\beta-1}dm \tag{6}$$

We now make two approximations, first that β is constant throughout the mixed region, and second that the burning only occurs at one mass point. Since the lithium reaction rates are such very strong functions of temperature that the burning really takes place only in a small region at the base of the convective envelope, this is a fairly good approximation. Therefore we replace $\frac{1}{(\Delta m)}\int_{m_1}^{m_2}(\frac{N_7(m)}{N_7(0)})^{\beta-1}dm$ with $[\frac{1}{(\Delta m)}\int_{m_1}^{m_2}(\frac{N_7(m)}{N_7(0)})dm]^{\beta-1}$ and obtain:

$$[\frac{r_{7,6}(t)}{r_{7,6}(0)}]^{-1} \approx [\frac{N_7(t)}{N_7(0)}]^{\beta-1} \tag{7}$$

where all qauntities are stellar surface observed quantities. We here note the important feature that this can be made an exact *upper bound* for $r_{7,6}$ if we use the maximum value for $\beta = 76$. This statement follows from the inequality:

$$[\frac{1}{b-a}\int_a^b f(x)dx]^p \leq \frac{1}{b-a}\int_a^b [f(x)]^p dx \quad \text{for } p > 1 \tag{8}$$

which is a special case of Hölder's inequality (see, for example, James and James 1976, p. 182). Finally then:

$$[\frac{r_{7,6}(t)}{r_{7,6}(0)}]^{-1} \geq [\frac{N_7(t)}{N_7(0)}]^{75} \tag{9}$$

or

$$r_{7,6}(t) \leq r_{7,6}(0)[\frac{N_7(t)}{N_7(0)}]^{-75} \tag{10}$$

III. Predictions from Observations

To place our predictions on a solid theoretical as well as observational basis, we will use the simulations of D'Antona and Mazzitelli (1984) to fit a predicted ^7Li depletion curve to the observed data (figure 1) and using equation (10) and an initial value for $r_{7,6}(0) = .10$, we obtain a relation between $r_{7,6}$ and T_{eff}. We note that all other fits of the observational data have curves which fall slightly above this and so our choice of this fit ensures again that we are obtaining an absolute upper bound on $r_{7,6}$. What we find is complete lithium-6 destruction below $log(T_{eff}) = 3.8$ (see Table 1). Since the $r_{7,6}(T_{eff})$ curve can be expected to have roughly the same shape as $N_7(T_{eff})^{-1}$, $log(T_{eff}) = 3.8$ represents the beginning of a very sharp drop in $r_{7,6}$, if indeed there is a large primordial ^6Li dominance.

IV. Predictions and Observations

From Table 1 we can see that only in halo dwarf stars with $log(T_{eff}) \geq 3.8$ can we be sure of seeing any effects of an increased primordial lithium-6 abundance. There are so far a few stars observed in this range (see Table 2). The observed total lithium abundances are within quoted errors of our predicted lower bounds, given an initial value for $r_{7,6}$ of .10. So far, no measurements of $r_{7,6}$ have been made in the $log(T_{eff}) \geq 3.8$ region. Measurements at $log(T_{eff}) = 3.77$ and 3.74 have turned up ratios of > 10 (Maurice, Spite and Spite 1984). These are within our absolute upper bounds. We thus call for a measurement of $r_{7,6}$ for LP608-62, G64-12, BD+3°740, HD84937, or some higher T_{eff} very low metallicity halo dwarf. This measurement should give us a clear cut test of the late decaying massive particle scenario, and a new test of big bang nucleosynthesis in general, since a primordial ^6Li abundance is forbidden by the "standard" BBN model.

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Captions

Fig. 1–This graph scatterplots several sets of observations:
RBM-Beckman, Rebolo, and Molaro 1987
HD-Hobbes and Duncan 1987
SMS-Spite, Maillard, and Spite 1984
SS-Spite and Spite 1982
The solid line represents the model predictions of D'Antona and Mazitelli(1984) normalized to Hobbs and Duncan's (1987) "plateau" value of $log(N_7)_o = 2.06$.

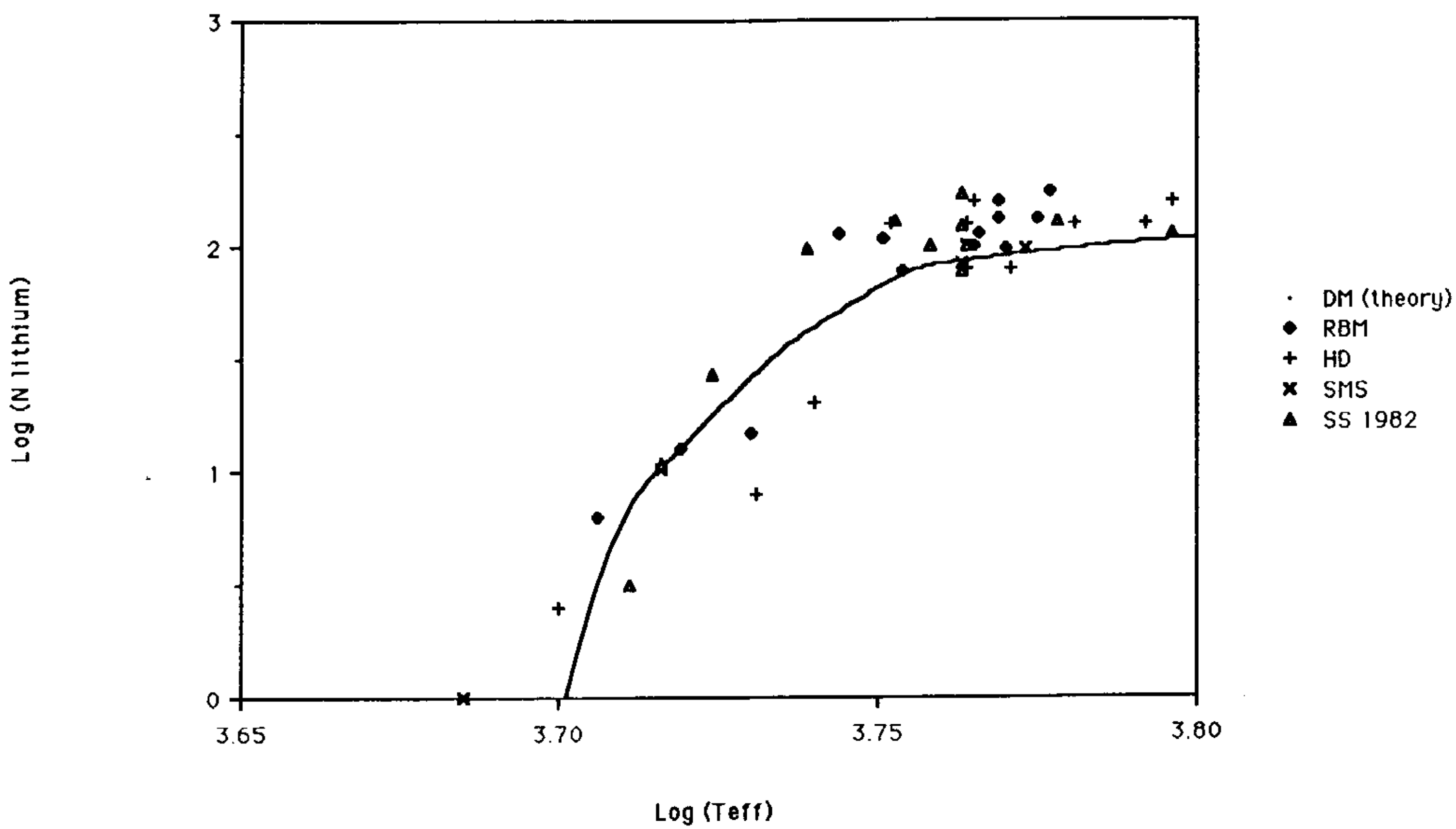
Fig. 2–We show $N_a < \sigma_7 v >$ (in $cm^3 sec^{-1} mole^{-1}$) and $N_a < \sigma_6 v >$ vs. T where $\sigma_{7\ or\ 6}$ is the cross section for the reaction $^7Li(p,^3He)^4He$ or $^6Li(p,\alpha)^3He$ respectively. Rates are taken from the emperical formulas in Fowler, Caughlan, and Zimmerman(1975). Note the extremely strong temperature dependance.

Fig. 3–$\beta \equiv \frac{<\sigma_6 v>}{<\sigma_7 v>}$, the ratio of the Lithium destruction rates is plotted versus T. Note the relatively slow variation over temperature.

Table 1–Lithium depletion predictions of the models of D'Antona and Mazzitelli (1984) for low solar mass stars with metallicity Z = .001 and age 10^{10} years. Also shown are the resulting upper bound values implied for $r_{7,6}$.

Table 2–A compilation of measurements of stars with very low metallicity $[Fe/H] \leq 1.4$ and $log(T_{eff}) \approx 3.80$. Observers are:
RBM-Rebolo, Beckman, and Molaro 1987
SSPC-Spite, Spite, Peterson and Chaffee 1987
HP-Hobbs and Pilachowski 1987
HD-Hobbs and Duncan 1987
B-Boesgaard 1985

Figure 1



3
2
1
0
Log (N lithium)
3.65
3.70
3.75
3.80
Log (Teff)
DM (theory)
RBM
HD
SMS
SS 1982

Figure 2

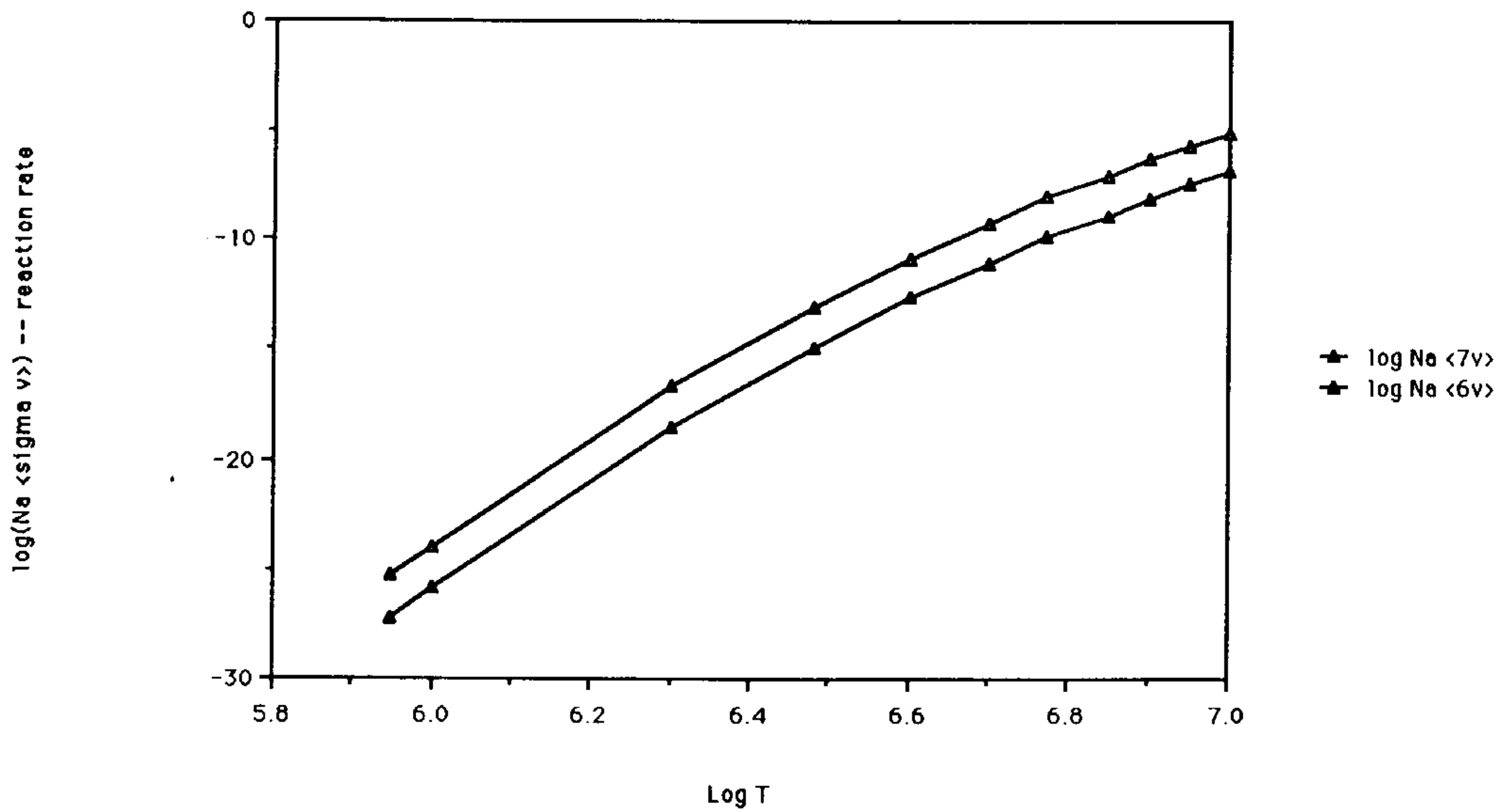

log(Na <sigma v>) -- reaction rate
0
-10
-20
-30
5.8
6.0
6.2
6.4
6.6
6.8
7.0
Log T
log Na <7v>
log Na <6v>

Figure 3

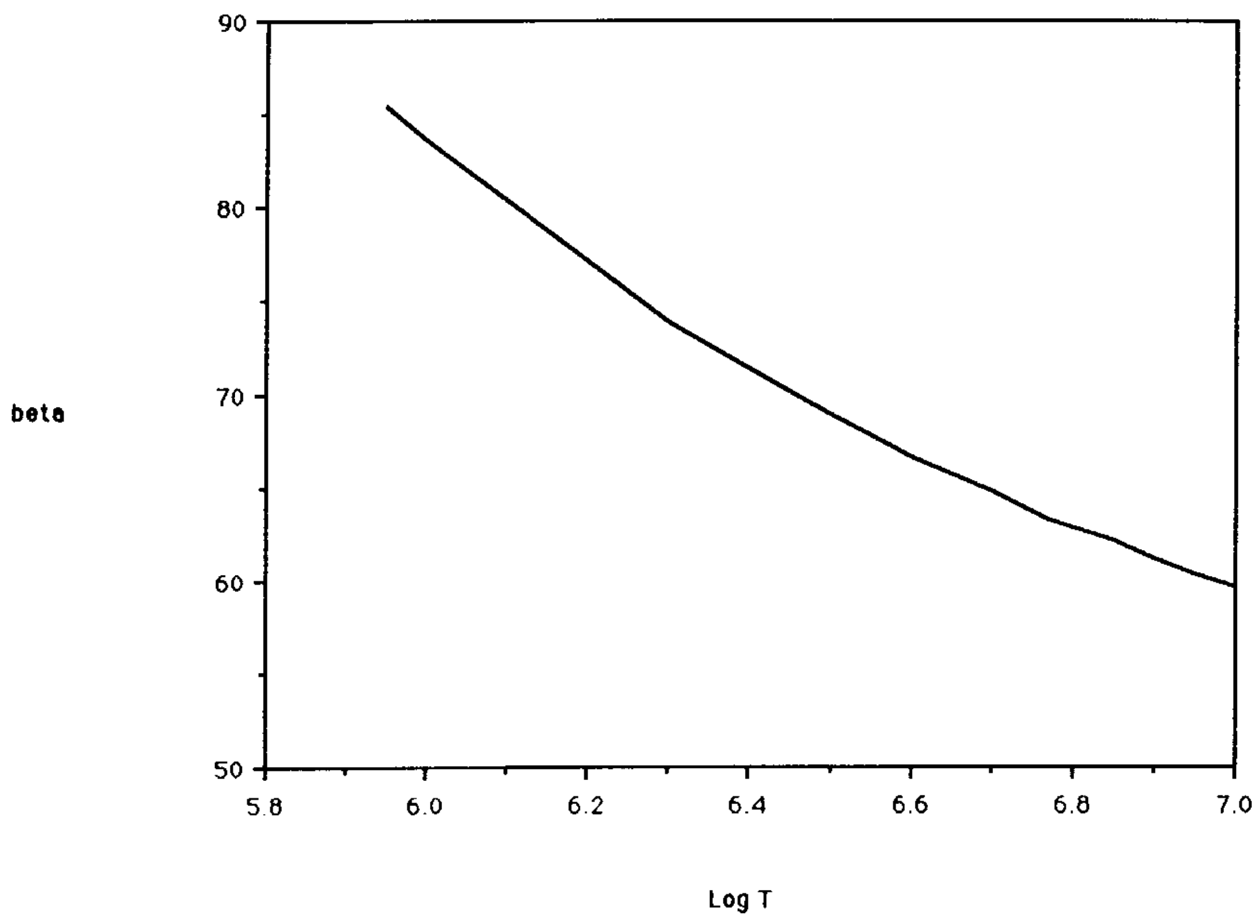


Table 1

T_{eff}	$\frac{N_7}{(N_7)_\odot}$	$r_{7,6} \leq$
3.672	4×10^{-9}	∞
3.714	0.081	∞
3.738	0.346	∞
3.758	0.707	2×10^{11}
3.802	0.965	1.45

Table 2

Star	$log(T_{eff})$	$log(N_6+N_7)$ (observed)	$r_{7,6} \leq$ (predicted)[a]	$log(N_6+N_7)$ (predicted)	Observers
G64-12	3.80	$2.23 \pm .20$	1.45	$2.28 \pm .12$	RBM
	3.80	$2.24 \pm .06$			SSPC
BD+3°740	3.80	$2.07 \pm .19$	1.45	$2.28 \pm .12$	HP
LP608-62	3.80	$2.20 \pm .15$	1.45	$2.28 \pm .12$	HD
HD84937	3.80	$2.15 \pm ?$[b]	1.45	$2.28 \pm .12$	B

a) assuming $r_{7,6}(0) = .1$ and $r_{7,6}(t) \approx [\frac{N_7(t)}{N_7(0)}]^{-75}$

b) no quoted uncertainty