THE ASTROPHYSICAL JOURNAL, Vol. 159, February 1970


# THE LITHIUM ISOTOPE RATIO IN DELTA SAGITTAE


## ABSTRACT

The apparent Li isotope ratio has been determined from measurements of the shift of the center of gravity of the Li doublet at λ6707 on two 4 Å $mm^{-1}$ spectrograms of δ Sge. The $^6$Li content is found to be 12 ± 6 percent of the total Li. High-energy spallation reactions predict about 30 percent $^6$Li. The discrepancy can be understood in terms of post–main-sequence dilution.


The eclipsing binary δ Sge ($m_v$ = 3.8) consists of an M2 Ib-II star and an A-type companion with a period of 3725 days (Hynek 1942; McLaughlin, Weston, and Chadwick 1952). The abundance ratio of Li/Ca has been determined for the M star (Merchant 1967). On the assumption of solar Ca abundance (Lambert and Warner 1968), the Li abundance is log $N$(Li) = +1.63, where log $N$(H) = 12.00. It is one of the few lithium-rich M stars with a Li content about 10 times the solar value. This abundance is 1–2 orders of magnitude less than that found in the T Tauri stars (Bonsack and Greenstein 1960). The progenitor of the M giant presumably was of an earlier main-sequence spectral type than the A-type companion. There are no observations of the Li abundances or isotope ratios in normal stars of such high temperatures.

TABLE 1

STELLAR LINES MEASURED

| λ(Å) | Element | Excitation Potential (eV) | λ(Å) | Element | Excitation Potential (eV) | λ(Å) | Element | Excitation Potential (eV) |
|---|---|---|---|---|---|---|---|---|
| 6039.69.... | V | 1.06 | 6325.22.... | Ti | 0.02 | 6554.23.... | Ti | 1.44 |
| 6064.63.... | Ti | 1.04 | 6358.69.... | Fe | 0.86 | 6556.07.... | Ti | 1.45 |
| 6119.50.... | V | 1.06 | 6452.35.... | V | 1.19 | 6574.24.... | Fe | 0.99 |
| 6126.22.... | Ti | 1.06 | 6497.69.... | Ti | 1.44 | 6605.98.... | V | 1.19 |
| 6134.58.... | Zr | 0.00 | 6498.95.... | Fe | 0.96 | 6710.31.... | Fe | 1.48 |
| 6135.36.... | V | 1.05 | 6531.44.... | V | 1.21 | 6743.12.... | Ti | 0.90 |
| 6143.23.... | Zr | 0.07 | | | | | | |

The apparent isotope ratio can be determined from measurements of the center of gravity of the resonance doublet at λ6707 (Herbig 1964). Since the separation of two isotopic doublets is only 0.158 Å, high-dispersion spectrograms are necessary. The two spectrograms used to determine the Li abundance and now the isotope ratio were obtained with the 160-inch coudé camera of the 120-inch reflector on Kodak 103a-F emulsion at a dispersion of 4 A $mm^{-1}$ widened to 0.8 mm. Reproductions of these spectrograms can be seen in Figure 3 of the paper by Merchant (1967).

The Li doublet at λ6707 is a 0.0-eV transition of neutral Li; in δ Sge it has a measured equivalent width of 350 mÅ. Lines were selected between 6000 and 6750 Å to determine the stellar radial velocity which fulfilled the following criteria: (1) line strength is comparable with the Li line, i.e., central absorption between 50 and 70 percent of the continuum; (2) line is formed by a neutral atom; and (3) excitation potential of the transition is less than 1.5 eV. Lines thus selected will reduce layer effects arising from the place of formation of the Li line and the comparison stellar lines. In addition, the lines used had no blending atomic or molecular lines within ±0.4 Å as listed by Davis (1947) for β Peg. A list of the lines used and their excitation potentials are given in Table 1.

The Li line itself is strong, and therefore its measured position is probably little affected by the weak blending lines of TiO in the region. The line is a doublet of separation 0.152 Å, with the transition value of the blueward line being twice that of the redward one. All measurements were made on a Grant profile-display engine. The center of gravity of the Li line was measured by lining up the two display profiles near half-intensity.

The positions of seventeen strong Ne comparison lines were measured and fit to a cubic expression to determine the dispersion at each wavelength. The stellar radial velocity was found by using four different sets of standard wavelengths for the measured lines. Two sets of laboratory wavelengths were used: the *Revised Multiplet Table* (RMT) and the M.I.T. wavelength table, and two sets of solar wavelengths: the Second Revised Rowland table and the new Kitt Peak solar wavelengths. The Kitt Peak wavelengths are also measured with a Grant measuring engine and were kindly supplied to me in advance of publication by Dr. Keith Pierce.

Table 2 gives the wavelength determined for the Li line on each plate as reduced with the four different sets of wavelengths. The probable errors per line and the number of lines used are also listed. The results agree very well for the four sets of wavelengths,

TABLE 2

APPARENT LITHIUM WAVELENGTHS

| | EC-170 | | | EC-4232 | | | MEAN |
|---|---|---|---|---|---|---|---|
| WAVELENGTH SCALE | $\lambda_{Li}$(6707+) | p.e.(Å) | No. | $\lambda_{Li}$(6707+) | p.e.(Å) | No. | $\lambda_{Li}$(6707+) |
| Solar: | | | | | | | |
| Rowland......... | 0.828 | 0.016 | 18 | 0.833 | 0.018 | 16 | 0.830 |
| Kitt Peak......... | 0.831 | 0.007 | 12 | 0.836 | 0.013 | 12 | 0.833 |
| Laboratory: | | | | | | | |
| RMT............ | 0.826 | 0.012 | 16 | 0.836 | 0.012 | 14 | 0.831 |
| M.I.T............ | 0.828 | 0.013 | 15 | 0.829 | 0.012 | 13 | 0.829 |

but the smallest probable errors are found when the Kitt Peak solar wavelengths are used. The mean of the two plates is given in the last column.

Since the solar wavelengths are measured from observations at the center of the disk rather than in integrated light and are subject to a small gravitational redshift which the laboratory Li line is not, the laboratory wavelengths are to be preferred. In the absence of a strong reason to select one set of laboratory wavelengths over the other, an average was taken of the two means given in the last column of Table 2. The center-of-gravity wavelength thus determined for the Li line is 6707.830 $\pm$ 0.009 Å. The apparent $^6$Li/$^7$Li isotope ratio is 0.135. Of the total amount of Li, 12 $\pm$ 6 percent is $^6$Li compared with $\sim$30 percent expected from pure high-energy spallation processes (Bernas *et al.* 1967).

This measured amount of $^6$Li is different from zero by only 2 times the probable error. But it is not unreasonable to expect this evolved star to have 12 percent $^6$Li. The most straightforward explanation involves post–main-sequence convective dilution in a massive star. Iben (1966) has calculated that by the time a 5 $M_\odot$ star leaves the main sequence it will have destroyed (by $p,\alpha$ reactions) all its Li except the $^7$Li in the outer 1.2 percent of the stellar mass and the $^6$Li in the outer 0.7 percent. As the star evolves to the red-giant tip, an outer convective zone forms and deepens to extend over the outer 71 percent of the star in mass. If there is thorough mixing, the $^6$Li will be diluted by about twice as much as the $^7$Li. Thus, if the spallation isotope ratio is present in the outermost layer while the star is on the main sequence, we would expect to find the amount of $^6$Li reduced to about 15 percent of the total Li when the star becomes a red giant. This is well within the quoted error of the $^6$Li content in $\delta$ Sge.

Other more speculative notions which can explain the low $^6$Li content include (1) an altered initial isotope ratio due to threshold-energy effects as discussed by Conti (1970), (2) formation of new $^7$Li in the interior as suggested by Cameron (1955), and (3) the surface destruction of $^6$Li by suprathermal protons as discussed by Reeves and Audouze (1968). It seems unnecessary to invoke these less certain explanations inasmuch as convective dilution can account for the $^6$Li content provided that $\delta$ Sge is a massive star. It should be possible to determine the mass, since this star is thought to be an eclipsing binary with primary eclipses in early 1969 and early 1979.

I should like to thank Dr. George H. Herbig and the Lick Observatory for lending me the two spectrograms of $\delta$ Sge. I am indebted to Dr. Peter Bodenheimer for valuable comments on the original manuscript.

ANN MERCHANT BOESGAARD

1969 June 27; revised 1969 August 18

INSTITUTE FOR ASTRONOMY
UNIVERSITY OF HAWAII

## REFERENCES

Bernas, R., Gradsztajn, E., Reeves, H., and Schatzman, E. 1967, *Ann. Phys.*, **44**, 426.
Bonsack, W. K., and Greenstein, J. L. 1960, *Ap. J.*, **131**, 83.
Cameron, A. G. W. 1955, *Ap. J.*, **121**, 144.
Conti, P. S. 1970 (in press).
Davis, D. N. 1947, *Ap. J.*, **106**, 1.
Herbig, G. H. 1964, *Ap. J.*, **140**, 702.
Hynek, J. A. 1942, *Ap. J.*, **95**, 324.
Iben, I., Jr. 1966, *Ap. J.*, **143**, 483.
Lambert, D. L., and Warner, B. 1968, *M.N.R.A.S.*, **140**, 197.
McLaughlin, D. B., Weston, E., and Chadwick, M. 1952, *Pub. A.S.P.*, **64**, 300.
Merchant, A. E. 1967, *Ap. J.*, **147**, 587.
Reeves, H., and Audouze, J. 1968, *Ap. Letters*, **1**, 197.