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Abstract. Absolute production rates of He^3 and Ne^{21} in L-chondrites have been determined from a least-squares fit of noble-gas to Al^{26} data, for meteorites of radiation age <2 Myr. in which Al^{26} has not been built up to saturation levels. The values obtained, 2.48±0.23 and 0.466±0.031 ccSTP g^{-1} Myr^{-1}, are 24% higher than conventional values, based on H^3 measurements. Apparently all published radiation ages of stony meteorites based on conventional production rates are too high by 24%.

INTRODUCTION

Radiation ages of meteorites are based on measurement of a radioactive and a stable cosmogenic nuclide. The radioactive nuclide measures the effective cosmic-ray flux in the meteorite, while the stable nuclide integrates this flux over time. If S is the concentration of the stable nuclide, in atoms/g, and A_o^r is the saturation activity of the radioactive nuclide, in disintegrations $sec^{-1}g^{-1}$, then the radiation age t equals:

$$t = (S/A_o^r)(P_r/P_s) \quad (1)$$

where P_r and P_s are the production rates of the radioactive and stable species, in atoms $sec^{-1}g^{-1}$ (Anders, 1963).

Unfortunately, P_r and P_s are hard to evaluate. They involve the cosmic ray flux as a function of time and energy and the production cross sections as a function of energy for all nuclear reactions leading to the two nuclides in question. Much of this information is not known.

In order to circumvent this difficulty, one usually chooses pairs of nuclides that are isobaric or at least fairly close in mass number: He^3-H^3, Ne^{22}-Na^{22}, Ne^{21}-Al^{26}, Ar^{36}-Cl^{36}, Ar^{38}-Ar^{39}, and Kr^{78}-Kr^{81}. One can then assume, with some justification, that the cross sections of both nuclides have the same energy dependence for all relevant target nuclides. P_r/P_s then simplifies to the ratio of two averaged cross sections, which may be determined in the laboratory for a suitable target element and bombarding energy.

In practice, even further simplifications are made. Measurements of radioactive nuclides are often unavailable, and it has therefore become customary to assume constant cosmic-ray fluxes for all meteorites, and to calculate radiation ages from stable nuclides alone, using fixed production rates. For chondrites at least, this is not a bad assumption, because their H^3 and Al^{26} contents are constant to ±15% in the majority of cases (Begemann _et al._, 1959; Geiss _et al._, 1960; Goebel and Schmidlin, 1960; Bainbridge _et al._, 1962; Begemann, 1966; Heymann and Anders, 1967; Fuse and Anders, 1969).

The ages derived by different methods are reasonably consistent with each other, and thus there is no reason to suspect a gross error in the above assumptions. Nonetheless, it is perhaps a little disconcerting to realize that the radiation age scale for stony meteorites rests almost entirely on eight H^3 measurements in chondrites (see Kirsten _et al._, 1963, for references) and an H^3/He^3 production ratio of 0.5 observed in the proton bombardment of iron (Schaeffer and Zähringer, 1958). From these data, an average He^3 production rate of 2.00×10^{-8} ccSTP g^{-1} Myr^{-1} has been derived for ordinary chondrites (Kirsten _et al._, 1963). Nearly all other dating methods for stones are directly or indirectly tied to this rate. For example, the Ne^{21} production rate in L-chondrites (0.377 ccSTP g^{-1} Myr^{-1}; Heymann _et al._, 1968; Cobb, 1965, quoted by Heymann, 1967) has been derived from the above value by way of the observed average He^3/Ne^{21} ratio of 5.3 (Heymann, 1967).

Kruger and Heymann (1968) have pointed out, however, that the H^3/He^3 production ratio depends on the neutron-to-proton ratio of the target element. Using measured values for Mg, Si, and Fe, and an interpolated value for O, they estimate a H^3/He^3 production ratio of 0.63 for hypersthene chondrites. This corresponds to a He^3 production rate of 2.6×10^{-8} ccSTP g^{-1} Myr^{-1}, 30% higher than the conventional value.

CALCULATION OF ABSOLUTE PRODUCTION RATES

In view of these uncertainties, we have attempted to estimate absolute He^3 and Ne^{21} production rates without recourse to nuclear cross sections. Instead, we have used a cosmogenic radionuclide, Al^{26}, as an indicator of absolute age. The Al^{26} activity of a meteorite, A, is related to the saturation value after an infinitely long bombardment, A_o, by the equation of radioactive growth:

$$A = A_o(1-e^{-\lambda t}) \qquad (2)$$

Here λ is the decay constant of Al^{26} (0.94 Myr^{-1}) and $\underline{t}$ is the radiation age. When A is appreciably less than A_o, this equation can be used to determine $\underline{t}$, provided that A_o is known (Anders, 1962).

A_o values for each class can be obtained either by averaging observed Al^{26} contents in meteorites of long radiation age, or by using the empirical Al^{26} production rates of Fuse and Anders (1969). These A_o values represent averages over various meteorite sizes and sample depths, and may thus be inappropriate for samples from very small or very large meteorites. However, the distribution of measured values for chondrites (Figure 3 of Fuse and Anders, 1969) shows that 85% of all meteorites fall within ±15% of A_o.

The He^3 or Ne^{21} content of these meteorites is likewise proportional to age:

$$He^3 = P_3 t \qquad \text{and} \qquad Ne^{21} = P_{21} t$$

where P_3 and P_{21} are the respective production rates, in ccSTP g^{-1} Myr^{-1}. These production rates depend on the chemical composition of the meteorite. In view of the scarcity of meteorites with low Al^{26} contents, we shall find it expedient to pool all available data, normalizing all production rates to those in L-chondrites:

$$P_{3,N} = f_{3,NL} P_{3,L}$$

Here the subscript N refers to meteorites of class N, while $f_{3,NL}$ is a factor compensating for differences in chemical composition. It can be calculated from the production rate relations given by Mazor et al. (1970):

$$f_{3,NL} = [2.06(O+C)+100]_N/[2.06(O+C)+100]_L$$

and $$f_{21,NL} = [2.2Mg+1.35Al+Si+0.29S+0.17Ca+0.017(Fe+Ni)]_N/ /[2.2Mg+1.35Al+Si+0.29S+0.17Ca+0.017(Fe+Ni)]_L$$

Chemical symbols represent weight percentages of the corresponding elements in the meteorite. The use of production rate relations introduces some circularity into our argument, but this circularity is definitely second-order. Since nearly all meteorites to be considered are chondrites of essentially similar composition, the chemical factors are close to unity. Errors in the production rate relations thus will tend to cancel.

The primary criteria were Al^{26} content less than 85% of saturation value (i.e. radiation age $\lesssim$2.03 Myr and noble-gas contents corresponding to a radiation age less than 3 Myr). Several meteorites (Pantar, Isoulane, Shytal, and New Concord) met the latter criterion, but not the former, as shown by Al^{26} measurements of Fuse and Anders (1969), and Herman and Anders (unpublished work). We also eliminated obvious cases of diffusion losses of He^3 as shown by $He_c^3/Ne_c^{21} < 3$ (all carbonaceous chondrites; Cullison and Menow), one discordant case in which the Ne^{21} age was much shorter than the Al^{26} age (Menow), and two cases of a two-stage irradiation (Ivuna, Serra de Magé; Fuse and Anders, 1969).

The data are shown in Figures 1 and 2. On the whole, they fit a linear trend, the largest exceptions being Malotas, and especially Appley Bridge. The Al^{26} measurements on both meteorites were done with great care, and it would therefore be desirable to re-check the noble gas data. For the time being, we have fitted two regression lines to the data; one with and one without Appley Bridge. The data are given in Table 2.

DISCUSSION

The production rates found fall between the conventional ones of Kirsten *et al.* (1963) and the revised ones of Kruger and Heymann (1968). We have somewhat more faith in the rates calculated without Appley Bridge. They exceed the conventional He^3 and Ne^{21} rates by the same amount: 24±9% and 24±7%.

The error limits of our production rates probably are realistic estimates of their accuracy. The half-life of Al^{26} (0.738±0.029 Myr, Rightmire and Kohman, 1958) contributes an error of only 4%. The A_o estimate is somewhat more uncertain, owing to variations in the effective cosmic-ray flux. But such variations affect Al^{26} and He^3, Ne^{21} to about the same degree. Hence the errors tend to offset each other, especially in the region where the growth curve is approximately linear. Elsewhere they will contribute to the overall scatter, which is taken into account in the regression.

Allowing for the uncertainty in the Al^{26} half-life, we obtain the following error estimates:

He^3 2.48 ±0.23 ccSTP g^{-1} Myr^{-1}

Ne^{21} 0.466±0.031 ccSTP g^{-1} Myr^{-1}

Judging from these production rates, it would seem that all published radiation ages of stony meteorites based on conventional rates will have to be shortened by a factor of 0.81. Future work may permit still more accurate determination of absolute production rates.

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TABLE 1 Meteorites with low Al^{26} Contents

Meteorite	Class	Al^{26} dpm/kg	Ref	A_o dpm/kg	t Myr	He_c^3 ccSTP/g	Ne_c^{21} ccSTP/g	Ref	$f_{3,NL}$	$f_{21,NL}$
Cold Bokkeveld	C2	12.9±0.9	4	47.0±4.7	0.34±0.05	0.23	0.09	8		0.75
Mighei	C2	35.6±2.0	7	47.6±4.8	$1.48^{+0.44}_{-0.31}$	1.66	0.66	8		0.76
Nogoya	C2	6±3	4	47.1±4.7	0.15±0.08	0.16	0.055	8		0.76
Pollen	C2	31±6	4	48.6±4.9	$1.11^{+0.53}_{-0.35}$	1.14	0.40	8		0.78
Grosnaja	C3	43.3±1.7	4	53.1±5.3	$1.82^{+0.69}_{-0.42}$	0.88	0.70	8		0.87
Adhi Kot	E3	50.9±2.1	10	60.1±6.0	$2.01^{+0.96}_{-0.50}$	4.7	0.8	6	0.93	0.79
St. Marks	E5	33±3	4	60.1±6.0	0.86±0.14	1.3	0.3	1	0.93	0.85
Cullison	H4	41.8±4.8	11	60.1±6.0	$1.26^{+0.44}_{-0.31}$	0.79	0.55	2	1.00	0.93
Malotas	H	37.9±1.4	10	60.1±6.0	$1.07^{+0.21}_{-0.18}$	3.7	0.63	2	1.00	0.93
Timochin	H5	17.9±1.3	10	60.1±6.0	0.38±0.06	0.94	0.17	9	1.00	0.93
Ladder Creek	L6	39.7±2.4	10	65.6±6.6	$1.00^{+0.16}_{-0.15}$	1.55	0.32	2	1.00	1.00
Shaw	L6	20±2	4	67.7±6.8	0.39±0.06	0.90	0.22	3	1.00	1.00
Appley Bridge	LL6	48±2	4	65.8±6.6	$1.37^{+0.36}_{-0.27}$	1.76	0.30	3	1.00	1.00
Shergotty	Eu	66.4±3.1	7	81.0±8.1	$1.83^{+0.71}_{-0.43}$	4.9	0.52	5	1.10	0.79

1 Kirsten, Krankowsky and Zähringer, 1963
2 Hintenbeger *et al.*, 1964
3 Heymann, 1965
4 Heymann and Anders, 1967
5 Heymann, Mazor and Anders, 1968
6 Zähringer, 1968
7 Fuse and Anders, 1969
8 Mazor, Heymann and Anders, 1970
9 Ganapathy, unpublished work
10 Herman and Anders, unpublished work
11 Herzog, unpublished work

TABLE 2

Production Rates of He^3 and Ne^{21} in L Chondrites

Reference	Production Rate, 10^{-8} ccSTP g^{-1} Myr^{-1} He^3	Ne^{21}
Kirsten *et al.* (1963)	2.00	0.377*
Kruger and Heymann (1968)	2.60	0.491*
This work (without Appley Bridge)†	2.48±0.20	0.466±0.024
This work (with Appley Bridge)†	2.30±0.23	0.440±0.030

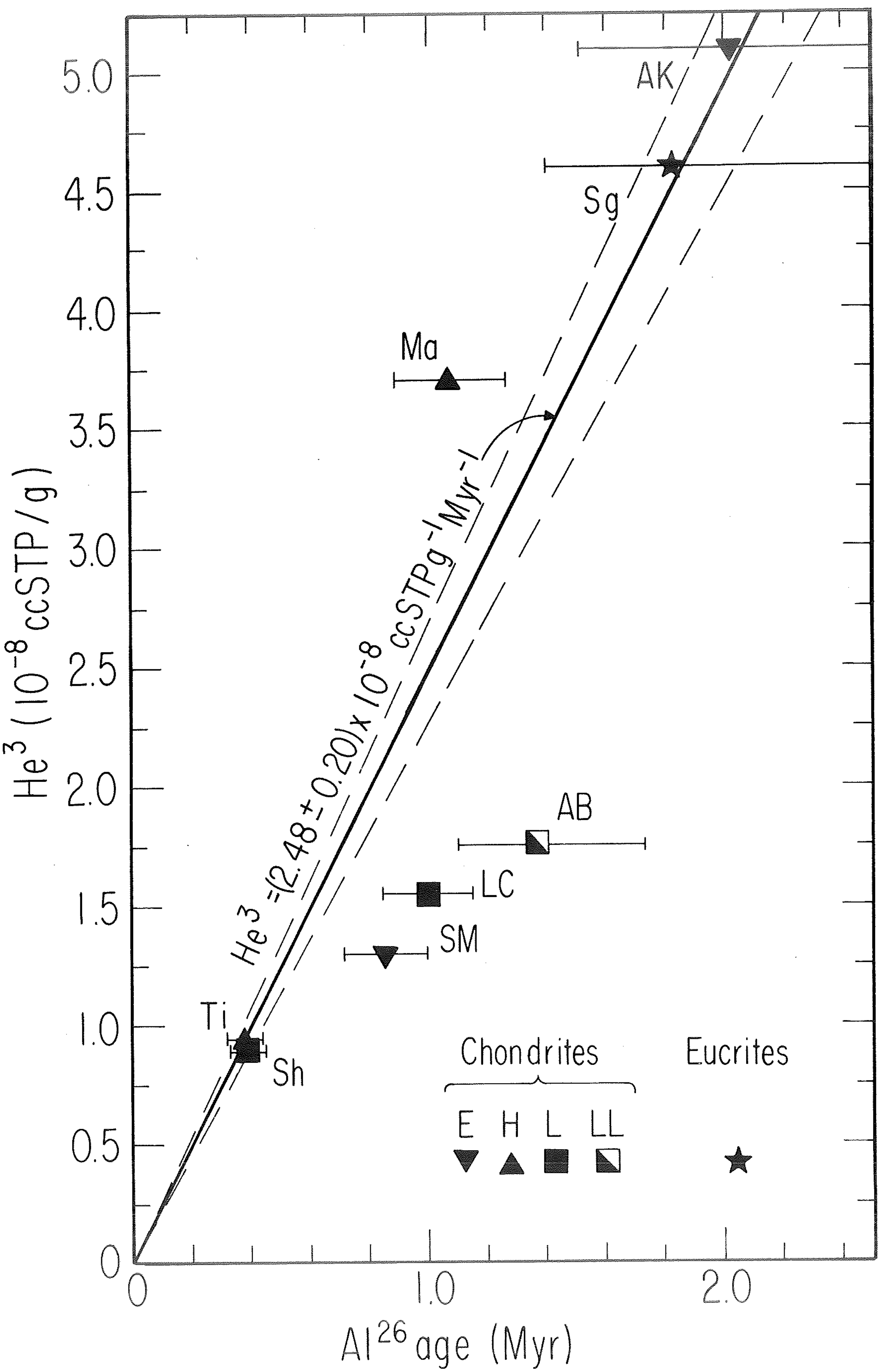
* Calculated from He^3 production rate on the basis of the average He^3/Ne^{21} ratio in L chondrites, 5.30.

† The errors quoted, which come directly from the regression analysis, do not include the uncertainty in the half-life of Al^{26} (see text).

FIGURE CAPTIONS

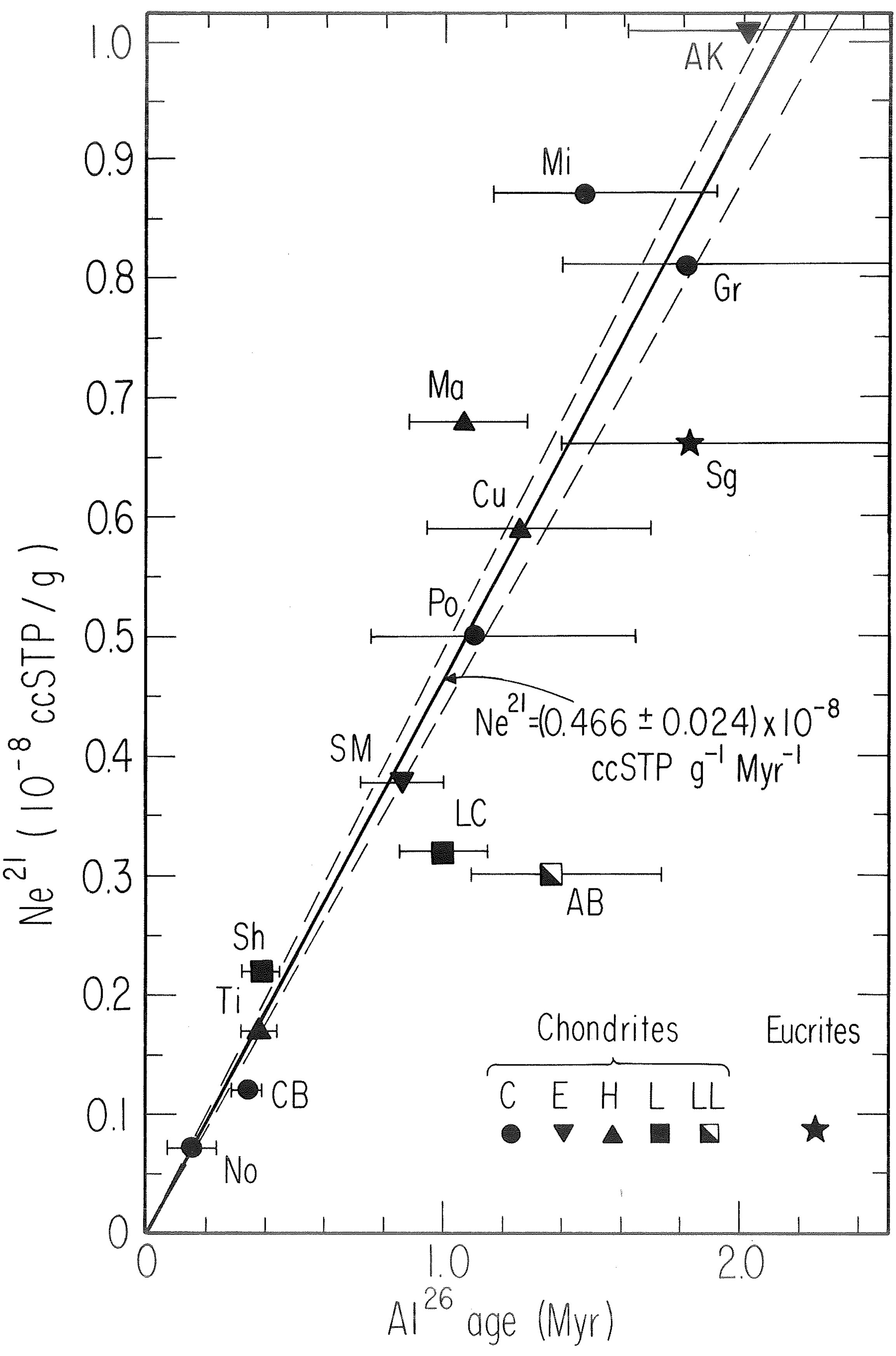
Figure 1. He^3 contents of stony meteorites, adjusted to level of L-chondrites (see text). Doubtful values are shown by open symbols. The regression line and its error limits are indicated by solid and dashed lines. Symbols: AB = Appley Bridge, AK = Adhi Kot, LC = Ladder Creek, Ma = Malotas, SM = St. Marks, Sh = Shaw, Sg = Shergotty, Ti = Timochin.

Figure 2. Ne^{21} contents of stony meteorites, adjusted to level of L-chondrites (see text). Other notation as in Figure 1 with the following additional symbols: CB = Cold Bokkeveld, Cu = Cullison, Gr = Grosnaja, Mi = Mighei, No = Nogoya, Po = Pollen.



5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0
He^3 (10^{-8} ccSTP/g)
0
1.0
2.0
Al^{26} age (Myr)
AK
Sg
Ma
$He^3 = (2.48 \pm 0.20) \times 10^{-8}$ ccSTPg^{-1}Myr^{-1}
AB
LC
SM
Ti
Sh
Chondrites
E H L LL
Eucrites

Fig. 1



1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Ne^{21} (10^{-8} ccSTP / g)
0
1.0
2.0
Al^{26} age (Myr)
AK
Mi
Gr
Ma
Sg
Cu
Po
Ne^{21}=(0.466 ± 0.024) x 10^{-8} ccSTP g^{-1} Myr^{-1}
SM
LC
AB
Sh
Ti
CB
No
Chondrites
Eucrites
C
E
H
L
LL

Fig.2