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Donald D. Clayton

*Clemson University*, claydonald@gmail.com

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INTERSTELLAR FOSSIL  $^{26}\text{Mg}$  AND ITS POSSIBLE RELATIONSHIP TO  
EXCESS METEORITIC  $^{26}\text{Mg}$ 

DONALD D. CLAYTON

Department of Space Physics and Astronomy, Rice University

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## ABSTRACT

I first demonstrate that the surprisingly large amount of  $^{26}\text{Al}$  detected in the interstellar medium by its gamma-ray emission implies that interstellar dust should carry in bulk a fossil anomaly at the level  $^{26}\text{Mg}^*/\text{Al} = 0.027$ , regardless of the chemical structure of that dust. I then demonstrate without invoking special chemistry for the  $^{26}\text{Mg}^*$  daughter how a linear correlation in  $^{26}\text{Mg}/^{24}\text{Mg}$  versus  $\text{Al}/\text{Mg}$  might be generated in macroscopic solids by a plausible three-stage process: (1) the mechanical aggregation of an average ensemble of Al-bearing dust particles that is postulated to be modestly enriched in the  $\text{Al}/\text{Mg}$  abundance ratio because the aggregated particles themselves are; (2) the extraction, perhaps but not necessarily by hot distillation, of almost all Mg, leaving an aggregate with a large  $\text{Al}/\text{Mg}$  ratio and a large  $^{26}\text{Mg}$  excess; (3) the uptake of normal ambient Mg by the resulting hot Al-rich solid as it cools in Mg-rich vapor. The sequence demonstrates that a linear correlation in solids between their  $^{26}\text{Mg}/^{24}\text{Mg}$  isotopic ratio and their aluminum enrichment does not in itself require the  $^{26}\text{Al}$  to have been still alive at the time the solids formed, but may instead be a fossil correlation inherited from interstellar dust. A correlation of the magnitude observed in meteorites was thought to be impossible prior to the *HEAO C* gamma-ray observations unless special chemistry was postulated to preserve the smaller  $^{26}\text{Mg}$  concentration then believed to exist in interstellar aluminum. I then question whether this sequence is relevant to actual meteoritic samples containing excess  $^{26}\text{Mg}$ . Although the quantitative possibility is demonstrated, its necessity is clouded by uncertainty over the nature of aluminum condensation during ejection from stars and by uncertainty over the actual chemical means by which the meteoritic CaAl-rich inclusions were created. The logical result of this demonstration is an added dimension in the astrophysical interplay of nucleosynthesis, chemical memory, the origin of the solar system, and meteorites.

*Subject headings:* abundances — interstellar: abundances — meteors and meteorites

## I. INTRODUCTION

In this paper I advance a plausible scenario for explaining a linear correlation found in some (but by no means all, or even most) solar system solids between their  $^{26}\text{Mg}/^{24}\text{Mg}$  isotopic ratios and their  $\text{Al}/\text{Mg}$  elemental abundance ratios. Although the particular scenario I will advance cannot yet be demonstrated to actually have occurred, and may be wrong in some details, the very existence of the argument refutes the commonly held belief that the correlation demonstrates that  $^{26}\text{Al}$  was necessarily alive in those solar system solids, that its decay within their present chemical structures enriched the  $^{26}\text{Mg}/^{24}\text{Mg}$  ratio *after* those minerals formed. I advance this argument not to be contentious but because the question has profound implications for astrophysics—namely, how and in what circumstances did the Sun and planetary bodies form? We have and continue to discover vastly more information relevant to the solar origin than it will ever be possible to obtain for the general problem of star formation. In particular we find recorded to some unknown degree in the many small bodies within the solar system a chemical history of events leading up to the collapse of the solar cloud. Those clues fingerprint the entire event. What may appear to be a technical detail to the nonspecialist, whether the obvious  $^{26}\text{Al}$  decay occurred *in situ* in the meteorites or in a prior generation of interstellar Al-bearing dust particles, becomes on close inspection a branch point in the general interpretation of the setting for the solar cloud and the sequence of events by which the Sun and planetary bodies formed. Far from being argumentative and contentious, the question is one of that set of fundamental

astronomical ones that must continuously be reinspected. We must not subject the precious, unique detail being measured with such brilliance in solar system samples to a set of interpretive ideas that is less probing. Another reason to advance the new argument to be presented is that it is made quantitatively possible by a new first in astronomy—the first detection ever of radioactivity within the interstellar medium. To assemble the chain of arguments needed, we must first reconsider that detection in the light of the objectives of this paper.

From the discovery of 1809 keV gamma radiation from the decay of  $^{26}\text{Al}$  ( $\tau = 1.06 \times 10^6$  yr mean lifetime) in the interstellar medium (Mahoney *et al.* 1982, 1984; Share *et al.* 1985) it has been demonstrated (Clayton 1984) that there is more  $^{26}\text{Al}$  in the interstellar medium than had previously been expected. About  $3 M_{\odot}$  of  $^{26}\text{Al}$  must be injected every  $10^6$  yr into the interstellar medium if it is distributed throughout the interstellar medium. The average isotopic ratio in the interstellar matter at the solar galactocentric radius is expected to lie in the range  $0.4 \times 10^{-5} < ^{26}\text{Al}/^{27}\text{Al} < 1.2 \times 10^{-5}$ , depending upon the source of the  $^{26}\text{Al}$ , its distribution throughout the Galaxy, and the interstellar sample (e.g., cold cloud, total gas) that carries the activity (Leising and Clayton 1985). The unexpectedly large interstellar  $^{26}\text{Al}/^{27}\text{Al}$  ratio may have dramatic impact on interpretations of the excess  $^{26}\text{Mg}$ , herein designated by  $^{26}\text{Mg}^*$ , that has been detected in aluminum-rich minerals within meteoritic inclusions. Wasserburg and Papanastassiou (1982) have written a fascinating account of the measurements of this excess and of the attempts to obtain data relevant to its interpretation. The ratio  $^{26}\text{Mg}^*/$

$\text{Al} = 5 \times 10^{-5}$  found in many minerals, especially anorthite, is significantly greater than the interstellar ratio observed today at the Sun's galactocentric radius. So if the  $^{26}\text{Al}$  was actually alive in the meteoritic minerals as we find them today, which has consistently been the interpretation of groups measuring the  $^{26}\text{Mg}$  excesses, then either the local value here was about 5 times greater  $4.6 \times 10^9$  yr ago when the solar system formed, or the solar system formed in a cloud fluctuation that was 5 times richer than average in  $^{26}\text{Al}$  concentration. Cameron (1984) has adopted the latter position, arguing that the solar formation was influenced by winds from asymptotic-giant-branch stars that he argues to be a plausible source of the interstellar  $^{26}\text{Al}$ . No doubt a similar interpretation could be based on winds from Wolf-Rayet stars, which Dearborn and Blake (1985) have suggested to be another good source of  $^{26}\text{Al}$ . So although the supernova-trigger injection of  $^{26}\text{Al}$  has now been virtually discarded following Clayton's (1984) demonstration that supernovae are not the sources of interstellar  $^{26}\text{Al}$  that Mahoney *et al.* (1982) detected, an amended version of that scenario for solar cloud collapse is still very possible and may be needed if the liveness of  $^{26}\text{Al}$  within the meteoritic minerals is demanded by the data. And that last question is the one I will address.

I will take a completely different stance—that  $^{26}\text{Mg}^*$  enrichment occurs during  $^{26}\text{Al}$  decay in the aluminum-bearing portions of interstellar dust, that it primarily does so much earlier in the grains' histories when a higher  $^{26}\text{Al}/^{27}\text{Al}$  ratio existed in the dust than exists in the steady state today, that a correlation of  $^{26}\text{Mg}^*$  with Al much larger than the correlation found in meteorites is thereby established in interstellar dust, and that this  $^{26}\text{Mg}^*/\text{Al}$  correlation may have been chemically remembered when the CaAl-rich inclusions are later assembled. The first three assertions will be established beyond reasonable doubt. The last supposition is the most speculative and controversial one. This idea has a long history in my work, beginning with its prediction (Clayton 1975) before the meteoritic  $^{26}\text{Mg}^*/\text{Al}$  correlation was even well established. But my purpose in this article will be to demonstrate how dramatically the plausibility of a fossil interpretation has been altered by the gamma-ray detection of interstellar  $^{26}\text{Al}$ . I will show that the fossil correlation is now quite plausible without the need to invoke the special chemical retentivities that I have introduced in previous attempts (Clayton 1977a, b, 1981a, 1982a) to escape the astrophysical problems of the *in situ* meteoritic decay theory. In those prior constructions I argued that  $^{26}\text{Mg}^*$  could not easily be removed from Al grains, so that Mg could be extracted more easily than  $^{26}\text{Mg}^*$ . The sequence I advocate here will not require that special chemical effect. Whether the indicated sequence can account for the observed mineral arrangements found in meteorites will not be addressed, however. That is best left to experts in meteorite microchemistry, who themselves regard this as a fundamental and highly uncertain question in meteoritics. But I will nonetheless conclude with an example scenario for an exciting hibonite inclusion studied by Hinton and Bischoff (1984).

A first task of this paper will concentrate primarily on evaluating the fossil correlation in the interstellar medium in order to provide an estimate of its size. This result will demonstrate a large  $^{26}\text{Mg}^*$  enrichment of the sites of interstellar aluminum. The major uncertainty is the nature and degree of aluminum condensation during stellar ejection. I will have to motivate the adoption of several assumptions of questionable validity in order to make a quantitative rather than a purely qualitative

estimate. The second major task will be the demonstration of the possibility of a new fossil interpretation of meteoritic data. The physical scenarios that I will advance for the latter purpose will establish the physical principle, but the many chemical questions related to the actual chemical constitution of observed inclusions cannot be evaluated here. The uncertainty about the origin of Al-rich meteoritic inclusions inhibits more detailed evaluation of those chemical questions. But because new isotopic and chemical data is appearing at a rapid rate, the ideas I will advance have the prospect of immediate confrontation with facts. The reader should also bear in mind that the *in situ*-decay theory for  $^{26}\text{Mg}^*$  excesses also faces severe confrontation with facts, because if it is correct it demands either that primitive inclusions within the same primitive carbonaceous chondrite differ in age by as much as  $10^7$  yr or that  $^{26}\text{Al}$  was distributed very inhomogeneously, more so than any other nuclide, within separate parcels of solar cloud. Either conclusion might be very hard to square with a self-consistent astrophysical picture of star formation.

## II. INTERSTELLAR DECAY AND INTERSTELLAR DEPLETION

The simplest astrophysical argument follows Clayton (1984), who calculated  $4.2 M_{\odot}$  of  $^{26}\text{Al}$  in the interstellar medium to account for the gamma radiation. A slightly smaller improved value for the gamma-ray flux (Mahoney *et al.* 1984) lowers that expectation to  $3.4 M_{\odot}$  of new  $^{26}\text{Al}$  every million years. The sources of the  $^{26}\text{Al}$  are probably novae, asymptotic-branch giants, or massive main-sequence stars (Wolf-Rayet stars). By contrast Clayton (1984) calculated that supernovae inject  $24 M_{\odot}$  of newly synthesized stable  $^{27}\text{Al}$  over the same  $10^6$  yr, accompanied by an almost negligible  $0.024 M_{\odot}$  of  $^{26}\text{Al}$  if the supernova production ratio is  $1 \times 10^{-3}$ . The third major source of interstellar aluminum is the return of old stable aluminum by stellar mass loss. Taking the time scale for replenishment of the ISM by stellar ejection to be  $\tau_{ej} = 4 \times 10^9$  yr and the total ISM Al to be the product  $X_{\odot}(\text{Al})M_{\text{ISM}} = (6 \times 10^{-5})(4 \times 10^9 M_{\odot}) = 2.4 \times 10^5 M_{\odot}$  as argued in Clayton (1984), the rate of Al return is  $60 M_{\odot}$  per million years. Before supporting these bulk galactic estimates with a calculation concentrating on the chemical evolution of the solar neighborhood within the framework (Clayton 1985a) of analytic models of that chemical evolution, I will describe why the  $^{26}\text{Al}$  decays in grains.

In general the most chemically refractory elements are those most depleted from the gas phase (Spitzer and Jenkins 1975). Of these Al has the largest depletion, typically  $10^{-3}$  of total Al within the diffuse clouds where the absorptions are detected. Why this is so constitutes a major astrochemical question, one that is germane to the issue of where  $^{26}\text{Al}$  decays. In broad terms it is suggestive that Al is the first major metal to condense in a gas in thermal equilibrium whose temperature is slowly decreased (e.g., Lattimer, Schramm, and Grossman 1978 and references therein). This led Field (1974) to suggest that the observed depletions were largely established by thermal condensation sequences, at least for the most highly depleted elements. Presumably this would have to have occurred as the matter was ejected from stars, rather than in interstellar gas-phase chemistry, because it is only in the former situation that the required sequences of falling temperature occur.

But this general approach is not in itself adequate for several reasons. The first is that in such sequences other slightly less refractory elements (consider in particular Mg and Si) would also condense at only slightly lower temperatures than Al

(about 300 K lower). Therefore, if  $\text{Al}_2\text{O}_3$  can nucleate and condense first, magnesium silicates should be also able to condense shortly thereafter on the preexisting particles. There is no natural way to stop the condensation sequence at high temperature. The Al depletions (typically  $10^3$ ) are about 30 times larger than typical Mg depletions and perhaps 100 times larger than typical Si depletions. A related problem is the destruction of interstellar dust by sputtering in the wake of shock waves in the ISM. Dwek and Scalo (1980) showed that the major mass of dust grains will be returned by this mechanism to the gas phase on a  $10^9$  yr time scale, shorter than the time scale for astration owing to reincorporation into stars. Many subsequent studies of this important and complicated cycling phenomenon exist (e.g., Draine and Salpeter 1979; Seab and Shull 1983). Of the many puzzles that attend this situation, I call attention especially to the apparent requirement of maintaining Al about 30 times less gaseous than Mg. Sputtering itself is not so selective.

I have frequently emphasized (Clayton 1981a, 1982b, 1985b) a way in which the combined action of thermal condensation sequences followed by sputtering may address this problem. If the most refractory elements do indeed condense first in such sequences, the refractory cores of ISM particles will carry a layered structure with increasingly less refractory elements condensing in layers around the more refractory elements. Because my purpose here is not to address this general problem so much as its possible implication for Al and Mg, I illustrate the point for those elements in Figure 1. The thermal chemistry suggests that  $\text{Al}_2\text{O}_3$  cores are likely to be surrounded partially by  $\text{MgAl}_2\text{O}_4$ , which is formed when MgO interacts with  $\text{Al}_2\text{O}_3$  at lower temperature, and surrounded still further by magnesium silicates at still lower temperature. Subsequent condensation, followed also by sticking of volatiles in interstellar clouds, may coat those refractory cores with volatile mantles. It is now obvious, granting this premise, that the bulk of the more abundant Mg must be sputtered away before the Al is even exposed. This results in Mg being more

gaseous in the ISM than Al. Only if the particle is totally destroyed will the Al be returned to the interstellar gas.

Notice the difference if one instead argues that stellar condensates will be amorphous, arguing (a point raised by a referee of this paper) that stellar ejecta lie on such high adiabats (low densities) that nucleation will be suppressed until a large supersaturation of condensibles finally results in rapid amorphous growths of metallic atoms and oxides having no organized chemical fractionation. The subsequent sputtering of those particles will eject Al, Mg, and even a more volatile element like P or Cl, equally. Depletion of Al by a factor of 30 more than Mg would then seem to require that Al sticks 30 times more efficiently to grains than does Mg in subsequent atom-grain collisions. Not only is this not chemically plausible, but the collisions of Al atoms with grains are not frequent enough to maintain a depletion factor of  $10^3$  in the face of  $(10^9 \text{ yr})^{-1}$  return rate of Al to the gas by sputtering. I have long used that argument (e.g., Clayton 1982b and references therein; D. D. Clayton, unpublished calculations) to argue that Al emerges from stars in condensed rather than gaseous form, and, moreover, that layered refractory cores such as in Figure 1 are needed to fractionate Al/Mg by a factor 30 in the gas phase. The argument that  $^{26}\text{Al}$  emerges from its sources largely in condensed form is of course essential to any fossil history of the  $^{26}\text{Mg}^*/\text{Al}$  correlation. Eighty-six percent of  $^{26}\text{Al}$  decays in the first 2 Myr after ejection from its source, so that if it were ejected instead in gaseous form the chances of getting into grains before decay might be slim, and in any case would not then be associated with aluminum.

There is yet another compelling argument that aluminum appears in condensed form from the first. It is the association of large isotopic anomalies with the element aluminum. The largest isotopic anomalies detected outside of very volatile elements are the 5%  $^{16}\text{O}$  excesses found in  $\text{MgAl}_2\text{O}_4$  (R. N. Clayton *et al.* 1977), the variations of up to 10% in  $^{50}\text{Ti}$  isotopes found in  $\text{CaO}\cdot 6\text{Al}_2\text{O}_3$  (Fahey *et al.* 1985; Ireland, Compston, and Heydegger 1985), and factor of 4 excesses in

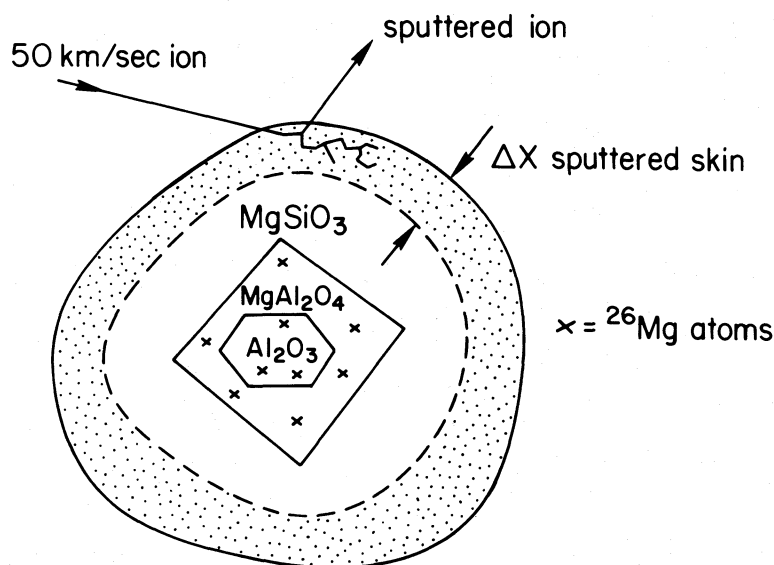


FIG. 1.—The first stardust to condense in a thermal sequence is Al-rich. That core is later buried by Mg and Si bearing mantles, here idealized as  $\text{MgSiO}_3$ . More volatile mantles are later added in dense clouds. These mantles protect Al from sputtering more than they do Mg. The  $^{26}\text{Mg}^*$  daughters of  $^{26}\text{Al}$  are shown as crosses. They are created largely in the first 2 Myr of the particle's interstellar life. Diagram prepared after Clayton (1981a).

$^{13}\text{C}$  found also in other  $\text{CaO}\cdot 6\text{Al}_2\text{O}_3$  minerals (Niederer, Eberhardt, and Geiss 1985). That these largest anomalies are found in first thermal condensate minerals strongly suggests that Al condensed upon ejection from a variety of sources and that it did not do so in amorphous structures. (Clayton 1981*b* described the application of chemical-memory theory to these anomalies.) Thus, is it any wonder that  $^{26}\text{Mg}^*$  variations are also found in Al-rich minerals!

My arguments here have been idealized for brevity, containing only elements of truth, but I will adopt them as compelling reason for considering their effect on the  $^{26}\text{Mg}^*/\text{Al}$  isotopic systematics. In principle, the condensation efficiency of new Al into supernova condensates ( $\equiv$  SUNOCONS; Clayton 1978) can differ from that of old Al into condensates from massive giant envelopes ( $\equiv$  STARDUST; Clayton 1978) and of new  $^{26}\text{Al}$  into nova dust ( $\equiv$  NOVACONS; Clayton and Hoyle 1976), and indeed, of every type of relevant stellar ejecta. To simplify in order to get at the principal aim of this paper, I take all Al condensation efficiencies to be equal. I will take the best-case assumption insofar as an interstellar  $^{26}\text{Mg}^*/\text{Al}$  correlation is concerned—namely that *all* Al condenses as it leaves stars in Al-rich refractory cores of ejected grains. This extreme assumption enables the calculation to follow. But it should be noted that that calculation will be only modestly altered in its numerical result if it is instead assumed only that a major fraction of all Al condenses in this form.

The interesting possibilities to be presented below admittedly depend upon the substantial correctness of these assumptions. If all Al is instead ejected in gaseous form, or if the condensates are instead amorphous and do not preferentially condense Al in comparison with Mg, an interstellar correlation of  $^{26}\text{Mg}^*$  with elemental Al will not occur. Advocates of that position must advance their own explanation of the depletion data and of the isotopic anomalies found specifically in aluminum. I hold it likely, however, that a substantial fraction of ejected Al condenses as I have assumed.

The individual grains emerging from stars will also range through a large spectrum of isotopic compositions, even if they are chemically similar in having  $\text{Al}_2\text{O}_3$ -rich refractory cores containing the Al and other unspecified refractory metals. Some will have condensed with no initial  $^{26}\text{Al}$ , whereas some, especially nova grains, may have very large initial  $^{26}\text{Al}/^{27}\text{Al}$  ratios (Clayton and Hoyle 1976). The Mg isotopic composition in the individual ejecta will also vary, so that it would be a very large task indeed to provide even a speculative approximation to the spectrum of stellar condensates. To avoid that uncertainty over microdetail, I take a statistical approach. I will later assume that an aggregate of a large number of random Al-bearing grains is brought mechanically together, constituting an average sample of well-mixed interstellar Al-bearing grains. In this way I treat the average ISM, considering it to be well mixed in its dusty types, and I will consider cosmochemical properties of that average. I will not call on any sorting mechanism to later separate one type of Al-bearing grain from another. Nor will I advocate, as many others have in search of a specific cosmochemical result, a special admixture from one source. With these preliminaries established, the excess  $^{26}\text{Mg}^*$  can be evaluated within the standard chemical memory type theory (Clayton 1978, 1982*b*).

It follows from the previous paragraphs that the decay  $^{26}\text{Al}(\beta^+ \nu)^{26}\text{Mg}^*$  occurs overwhelmingly inside interstellar grains. These produce the  $\gamma$ -rays detected today by *HEAO C* and *Solar Maximum Mission*. According to preceding argu-

ments those decays occur primarily in the refractory Al-rich cores. Although the major mass of grain mantles is eroded by interstellar sputtering on a  $10^9$  yr time scale (e.g., Dwek and Scalo 1980), the Al cores would have much longer lifetimes against sputtering and would be, in fact, destroyed instead primarily by reincorporation into stars (astration) with a mean lifetime of perhaps  $3 \times 10^9$  yr. Clayton (1985*b*) used the same arguments presented above to conclude that the layered nature of refractory condensation causes the interstellar Al to be sputtered about 10 times more slowly than the interstellar Mg. That rather speculative conclusion will be adopted here for purposes of numerical estimation of the size of the  $^{26}\text{Mg}^*$  fossil. Let us therefore temporarily ignore sputtering of the cores, assuming them to be destroyed only by astration. From the bulk Galactic estimates presented at the beginning of this section, it now can be concluded from direct astronomical observation that the injection ratio into the interstellar medium of eventual  $^{26}\text{Mg}^*$  derived from Al decay to total Al is

$$\frac{^{26}\text{Mg}^*}{\text{Al}} = \frac{3.4 M_{\odot} \text{ Myr}^{-1}}{24 M_{\odot} \text{ Myr}^{-1} + 60 M_{\odot} \text{ Myr}^{-1}} \approx 0.040. \quad (1)$$

In order to avoid reliance on this bulk Galactic estimate, Clayton (1985*b*) evaluated similar quantities within an analytic model of the chemical evolution of the solar neighborhood—specifically the  $k = 1$  model (Clayton 1985*a*) having  $\Delta = 1$  Gyr and  $\omega = 0.172(\text{Gyr})^{-1}$ , which yields a gas fraction  $\mu = 0.19$  in the solar neighborhood today. This analytic model has the property that the total mass density ( $43 M_{\odot} \text{ pc}^{-2}$ ) of the local Population I system (not the total dynamic mass, which is about twice as great) has increased by a factor 6.37 times the initial mass density of the local disk owing to the continuous exponential ( $f = f_0 e^{-\omega t}$ ) infall of metal-poor gas over the past 15 Gyr. This model is one of many giving reasonable agreement with local observables (Clayton 1985*a*). This model gives the value  $^{26}\text{Mg}^*/\text{Al} = 0.027$  to the local injection ratio in equation (1) if the results of Leising and Clayton (1985) are taken to require that the average local interstellar ratio demanded by the gamma-ray observations is  $^{26}\text{Al}/^{27}\text{Al} = 8 \times 10^{-6}$ . Because this analysis is more correct, even if less transparent, than equation (1), I will adopt  $^{26}\text{Mg}^*/\text{Al} = 0.027$  for the injection ratio, precisely  $^{26}\text{Al}/^{27}\text{Al}$  ejected from all stars. Notice especially that it applies to an average mixture of *all* interstellar Al-bearing grains, not to only one component. The ratio to newly synthesized aluminum is also shown by Clayton (1985*b*) to be  $P(^{26}\text{Al})/P(^{27}\text{Al}) = 0.065$ , requiring, if that production ratio is constant in time, that 4.7% of  $^{26}\text{Mg}$  was synthesized as  $^{26}\text{Al}$  parent. This is the first time that a reliable evaluation of that parentage has been possible. Its value is much larger than expected prior to the gamma-ray observations.

The conclusions and suppositions to be drawn from this discussion must be summarized explicitly:

1. The  $^{26}\text{Al}$  condenses along with all Al in the stellar outflows, probably as spinel ( $\text{MgAl}_2\text{O}_4$ ) or corundum ( $\text{Al}_2\text{O}_3$ ) cores of larger refractory layered particles (Clayton 1977*b*; Lattimer, Schramm, and Grossman 1978). This is a key assumption, because if it emerges gaseous or only in amorphous dust lacking Al/Mg fractionation, subsequent effects vanish.
2. The  $^{26}\text{Al}$  decays to  $^{26}\text{Mg}^*$  in those grains emerging from the  $^{26}\text{Al}$  sources, so that the  $^{26}\text{Mg}^*$  is physically associated with Al even though it behaves chemically as Mg. To remove  $^{26}\text{Mg}^*$  from Al requires subsequent chemical alteration.
3. If the ratios of stellar ejection rates are constant in time

and if astration is the major destruction mechanism of Al cores, then the steady state ratio residing in those Al cores is  $^{26}\text{Mg}^*/\text{Al} = 0.027$  on average. The ratio is much larger in the Al cores from the  $^{26}\text{Al}$  sources, and it is much smaller in the majority of the Al cores emerging from other types of stars that eject Al but no  $^{26}\text{Al}$ .

4. The interstellar grain types mix in the interstellar medium. I will take an average mixture. A representative collection of aluminum-bearing grains carries  $^{26}\text{Mg}^* = 0.027$  Al regardless of its Mg content. One cannot specify the magnitude of the associated isotopic excess in Mg without specifying the amount of common Mg in the collection of grains. But as a point of reference, in the solar abundances  $^{26}\text{Mg} = 1.388$  Al. The total fraction of  $^{26}\text{Mg}$  residing as  $^{26}\text{Al}$  extinct parent is  $^{26}\text{Mg}^*/^{26}\text{Mg}_\odot = 0.019$ , whereas the total fraction of  $^{26}\text{Mg}$  ever synthesized as  $^{26}\text{Al}$  parent is 4.7%. This number is far larger than expected before the gamma-ray observations.

It is possible conceptually to divide the steady state interstellar abundance of Mg into two parts: (1) the spike  $^{26}\text{Mg}^*$  in the aluminum having  $^{26}\text{Mg}^*/^{24}\text{Mg} = \infty$ ; (2) the remainder of the magnesium having

$$\begin{aligned} \left(\frac{^{26}\text{Mg}}{^{24}\text{Mg}}\right)_g &\equiv \frac{^{26}\text{Mg}_\odot - 0.019 ^{26}\text{Mg}_\odot}{^{24}\text{Mg}_\odot} \\ &= 0.981 \left(\frac{^{26}\text{Mg}}{^{24}\text{Mg}}\right)_\odot \equiv g \end{aligned} \quad (2)$$

where the subscript  $g$  = "ghost," the concept of the complementary pool defined for this problem by Clayton (1977b). In other words, the bulk of common interstellar Mg (solar Mg corrected for the  $^{26}\text{Mg}^*$  residing with the Al) has a large  $^{26}\text{Mg}$  deficiency equal to 1.9%. This negative anomaly is also much larger than expected prior to the gamma-ray observations. The Mg isotopic composition in a mixture of all dust is taken to be solar by definition. The value of  $g$  will be somewhat different if the average ejection ratio  $p = (^{26}\text{Al}/^{27}\text{Al})$  differs from 0.027 or if some fraction of the  $^{26}\text{Mg}^*$  is homogenized in the interstellar medium by sputtering of the central Al-rich cores of refractory grains. No particular assumption has been made about the chemical state and location of the bulk of interstellar magnesium.

### III. ALUMINUM-RICH AGGREGATES OF INTERSTELLAR DUST

Now imagine that at some later time, either in the interstellar medium, in the cloud collapse phase, or in a solar disk, an Al-rich aggregate of dust is collected. This is not sorting out one type of Al dust, but rather sorting of Al-bearing dust from other types of dust. Although this is a key step in the argument, to assess its effect we need not describe precisely how this comes about, except that it is some mechanical aggregation process that enriches by a modest factor the ratio  $(\text{Al} + ^{26}\text{Mg}^*)/\text{Mg}$ . The  $^{26}\text{Mg}^*$  is mechanically carried with the Al, so they are enriched together in a mechanical collection of Al-rich grains. (This is not the stage when the very Al/Mg-rich meteoritic minerals [e.g., anorthite] are formed, but preliminary events that have prepared a modestly enriched dust collection.) Many ways for this to happen are plausible, especially utilizing variations in the ratio of hydrodynamic drag to inertia for different classes of particles. The easiest way is if the superrefractory-rich core-mantle grains in which the bulk of Al resides are larger than those in a more populous class of small Mg-bearing grains, as Clayton (1980) suggested by a plausible

scenario, so that a mechanical collection of the former could then be deficient in the latter. But I am not calling for a process selecting one type of Al-bearing grain from another, although that too is not implausible. The very existence of chemical fractionation in primitive meteorites assures us that chemical fractionation during aggregation processes has been routine. Roughly 30% variations even in bulk ratios Al/Si and Mg/Si have long been used in classification schemes for primitive chondritic meteorites, with larger variations existing over finer scales (e.g., Michaelis, Ahrens and Willis 1969).

What is the Mg isotopic composition of the Al-rich mechanical mixture? Let  $p \equiv (^{26}\text{Mg}^*/\text{Al}) = 0.027$  and  $g = (^{26}\text{Mg}/^{24}\text{Mg})_g$  in the ghost, as in equation (2). Then the Al-rich aggregate contains a bulk isotopic ratio

$$\frac{^{26}\text{Mg}}{^{24}\text{Mg}} = p \left(\frac{\text{Al}}{^{24}\text{Mg}}\right) + g = 1.27p \left(\frac{\text{Al}}{\text{Mg}}\right) + g \quad (3)$$

which takes on the solar ratio  $(^{26}\text{Mg}/^{24}\text{Mg})_\odot = 0.1394$  when Al/Mg also takes the solar ratio  $(\text{Al}/\text{Mg})_\odot = 0.080$ . But if the Al/Mg ratio in the aggregate is increased by the factor  $[\text{Al}/\text{Mg}] = (\text{Al}/\text{Mg})/(\text{Al}/\text{Mg})_\odot$ , where the square bracket notation means the ratio normalized to the solar ratio, equation (3) can be written (with  $p = 0.027$ ) in the simpler form

$$[^{26}\text{Mg}/^{24}\text{Mg}] = 0.019[\text{Al}/\text{Mg}] + 0.981. \quad (4)$$

For example, if  $[\text{Al}/\text{Mg}] = 2$  has only doubled the Al/Mg ratio from its solar average, the  $[^{26}\text{Mg}/^{24}\text{Mg}] = 1.019$  shows the  $^{26}\text{Mg}/^{24}\text{Mg}$  isotopic ratio increased by 1.9%. This is a very large increase for such a modest Al enrichment. The large 10% increases in that ratio found in meteoritic anorthite WA (Lee, Papanastassiou, and Wasserburg 1977) could be produced in bulk in an aggregate having only  $[\text{Al}/\text{Mg}] = 6$ , even though the WA samples containing this anomaly have aluminum richness factors  $[\text{Al}/\text{Mg}] > 10^3$ .

We conclude that an Al-rich aggregate of interstellar dust will have a large bulk  $^{26}\text{Mg}$  excess if that aggregate is gathered before radiogenic  $^{26}\text{Mg}^*$  has been driven out, as given approximately by equation (4). In what follows the subscript  $a$  = aggregate will be attached to these quantities to explicitly designate the ratio as being the one applicable at the time of the Al-rich aggregate; viz.  $[\text{Al}/\text{Mg}]_a$ . This aggregate will be regarded as a parent of CaAl-rich inclusions to be derived from it by chemical alteration.

### IV. EXTRACTION OF MAGNESIUM

The excitement of these estimates will probably hinge on whether evidence of this  $^{26}\text{Mg}^*$  excess can be found in Al-rich minerals in meteorites. For this to be the case, the very Al-rich minerals found there will have to have chemically remembered that they were assembled from  $^{26}\text{Mg}$ -rich dust aggregates. This is certainly not implausible, because Al-rich minerals in meteorites apparently routinely remember 5% excesses of  $^{16}\text{O}$  and several percent excesses of  $^{50}\text{Ti}$ , both of which are believed to be chemically inherited from interstellar SUNOCONS (Clayton 1981b). If those isotopes could not be homogenized, one questions whether  $^{26}\text{Mg}$  could have been. To explore this possibility, imagine that the Al-rich aggregate described above found itself intact in a solar disk after interstellar-cloud collapse to form the solar system.

Let magnesium now be removed from the Al-rich aggregate, so that the Al/Mg ratio is increased by a factor  $f$  (fractionation). Most, but not all, of the Mg is extracted. Then  $[\text{Al}/\text{Mg}]_0 =$

$f[\text{Al}/\text{Mg}]_a$  is the new Al/Mg richness of the fractionated aggregate. A useful mental visualization of a physical process to achieve this might be distillation at very high temperature, which can evaporate most of the Mg. This step is envisioned as a way of creating the very large  $[\text{Al}/\text{Mg}]$  ratios that are found in meteoritic minerals. Meteoritic chemists generally favor this mechanism. It need not be distillation, however. Extraction of Mg in a melt would do just as well for the argument being made here. The result may be termed an Al-rich "solid," considering that the chemically altered aggregate is no longer microscopic.

Suppose that in this extraction process all isotopes of Mg are extracted equally. This is the simplest assumption, though not necessarily to be expected when different isotopes have different chemical history, as in the case here. (One will actually expect some mass-dependent fractionation, but our main idea will be clearer if that possibility is temporarily suppressed.) In that case, the isotopic composition of the now much more Al-rich aggregate remains as it was:

$$[^{26}\text{Mg}/^{24}\text{Mg}]_a = 0.019[\text{Al}/\text{Mg}]_a + 0.981, \quad (5)$$

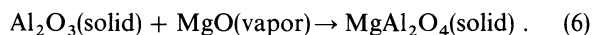
even though the Al/Mg ratio has been increased by the factor  $f$  because of the removal of magnesium. The reader must especially note the difference from Clayton (1977b, 1982a), in which works I attempted to postulate chemical grounds for  $^{26}\text{Mg}^*$  retention at this stage because the fossil anomaly was then not thought to be large enough. The gamma-ray astronomy has changed all that. So although those ideas remain interesting, what I show here is that they are no longer necessary for the construction of a fossil theory.

This sequence of events has produced very Al-rich-bulk samples that have large  $^{26}\text{Mg}$  isotopic excesses. These samples should probably be thought of as homogeneous in structure since they were heated to high temperature to remove the Mg and remain hot at this point in time. Separate aggregates may differ from one another by virtue of different  $[\text{Al}/\text{Mg}]_a$  enrichments in the initial dust aggregates or by different degrees of Mg extraction. The bulk of the Mg is ambient, perhaps a hot vapor at this time if distillation was the Mg extraction mechanism.

#### V. TAKEUP OF NORMAL MAGNESIUM

Following the preceding preparation of a very Al-rich solid having large  $^{26}\text{Mg}$  excess, a "false isochron" can be produced by dilution with normal Mg. If the Mg removed during the step described above, say by hot distillation, was mixed with the remainder of the Mg, that pool will be almost isotopically normal. I tentatively think of it as hot Mg vapor. It actually is expected to retain a small ghost, so I let  $(^{26}\text{Mg}/^{24}\text{Mg})' = g'$  be the Mg taken up at this time by the Al-rich aggregate, and I note that  $g'$  is probably much closer to  $g_\odot$  than to the ghost  $g$  in equation (2).

I envision next a process in which the hot Al-rich solid cools, say because of transport to a cooler region of a turbulent preplanetary solar disk (Morfill 1983). When this happens the less hot Mg vapor will now adhere to the solid by chemical bonding. Idealized the sequence might be the equilibrium sequence



This will not necessarily occur homogeneously throughout the solid because of rate-controlling factors. I anticipate that differ-

ent parts of the solid will be given different Mg enrichments by this process, which is illustrated schematically in Figure 2. Regions I, II, and III of that figure have different Mg uptake, which may remain inhomogeneous if the solid cools faster than the ambient Mg can diffuse through it (which is structurally solid rather than liquid in the low gas pressure within a solar disk.). A significant factor in the resulting inhomogeneity could be the sticking and merging of the initial particle to other particles in the probably turbulent gas (Morfill 1983). But in Figure 2 the possibilities are idealized for clarity to these three: region I takes up no ambient Mg and so remains the very Al-rich  $^{26}\text{Mg}$ -rich solid established earlier by Mg evaporation; region II takes up a significant amount of ambient Mg, thereby lowering the  $[\text{Al}/\text{Mg}]$  enrichment of region II; and region III takes up even more ambient Mg so that  $[\text{Al}/\text{Mg}]$  there is driven down to values of order unity. A little algebra will show that the  $^{26}\text{Mg}/^{24}\text{Mg}$  ratio is correspondingly diluted by the uptake of Mg.

We easily describe this dilution line by letting

$$r \equiv (\text{Mg added})/(\text{Mg previously in Al-rich residue}), \quad (7)$$

for then if  $(^{26}\text{Mg}/^{24}\text{Mg})_a$  is the initial isotopic ratio in the evaporative residue, then the new isotopic ratio after Mg uptake is

$$\frac{^{26}\text{Mg}}{^{24}\text{Mg}} = \frac{(^{26}\text{Mg}/^{24}\text{Mg})_a - g'r}{1 + r}. \quad (8)$$

This is cast into a linear dependence on the elemental abundance ratio by noting that

$$1 + r = \frac{(\text{Al}/\text{Mg})_0}{(\text{Al}/\text{Mg})} = \frac{f(\text{Al}/\text{Mg})_a}{(\text{Al}/\text{Mg})} \quad (9)$$

is the ratio of the  $(\text{Al}/\text{Mg})_0$  in the Al-rich residue after Mg distillation to the final Al/Mg ratio after Mg uptake; because then

$$\frac{^{26}\text{Mg}}{^{24}\text{Mg}} = \left( \frac{^{26}\text{Mg}}{^{24}\text{Mg}} \right)_a \frac{\text{Al}/\text{Mg}}{(\text{Al}/\text{Mg})_0} + g' \left[ 1 - \frac{\text{Al}/\text{Mg}}{(\text{Al}/\text{Mg})_0} \right] \quad (10)$$

shows the linear dependence of isotopic ratio on Al/Mg. The limits are clear. If no Mg was taken up,  $r = 0$ , and  $(\text{Al}/\text{Mg})$  remains equal to  $(\text{Al}/\text{Mg})_0$ , in which case  $^{26}\text{Mg}/^{24}\text{Mg}$  remains at its high value  $(^{26}\text{Mg}/^{24}\text{Mg})_a$ . In the limit  $r \rightarrow \infty$  so that  $(\text{Al}/\text{Mg}) \ll (\text{Al}/\text{Mg})_0$  then  $(^{26}\text{Mg}/^{24}\text{Mg}) \rightarrow g'$ , the isotopic composition of the taken-up Mg. For values in between, equation (10) shows a linear relation to  $(\text{Al}/\text{Mg})$ . This is, for example, what the linear relation in anorthite WA (Lee, Papanastassiou, and Wasserburg 1977) looks like, although it has been interpreted as an isochron resulting from simultaneous *in situ* decay of live  $^{26}\text{Al}$  in chemically different parts of an initially isotopically homogeneous inclusion. It is also of observational interest that the intercept  $g$  for primitive Mg-rich minerals can be expected to have a negative anomaly, a feature of a ghost already described by Clayton (1977b, 1981a) and sometimes found in the data (Wasserburg and Papanastassiou 1982). The size of that ghost cannot be predicted without defining the degree of homogenization between the initial large ghost  $g$  in equation (2) and the Mg removed from the Al-rich aggregates.

This idealized example demonstrates that a linear correlation within a suite of contiguous minerals of  $^{26}\text{Mg}/^{24}\text{Mg}$  with the Al/Mg ratio can be generated as a mixing line without need of live  $^{26}\text{Al}$ . The slope can easily be as great as the slope

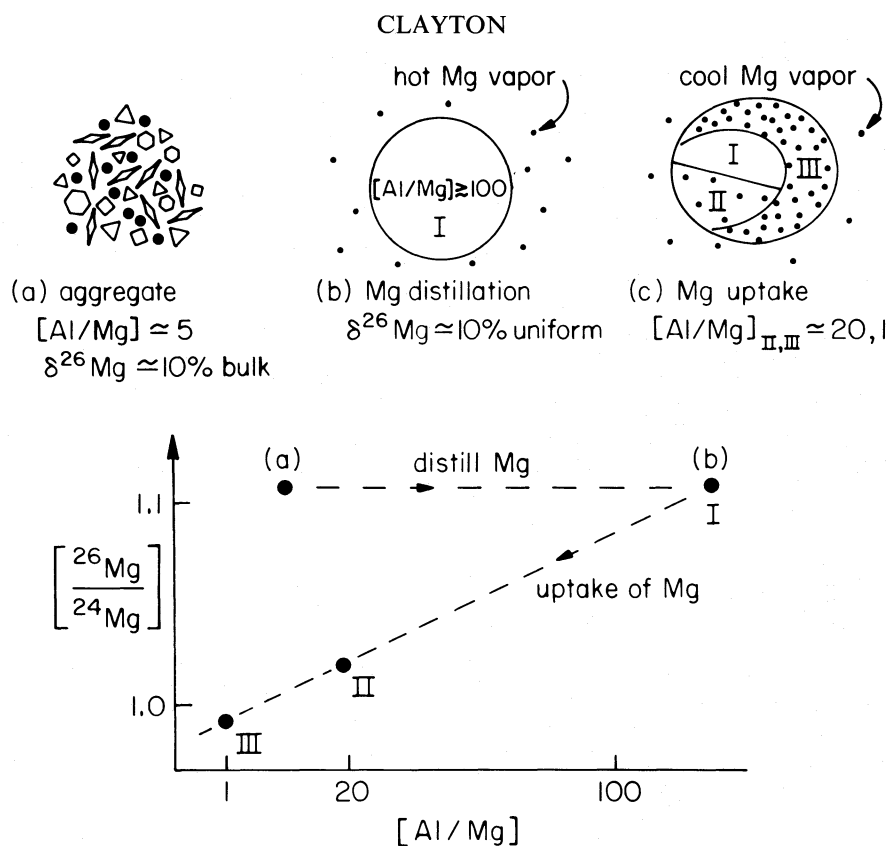


FIG. 2.—Idealized stages of the process: (a) a mechanical aggregation of dust particles having a bulk composition  $[Al/Mg] > 1$ ; (b) homogenization of the resulting aggregate and extraction of most of its magnesium by high temperature, probably by Mg evaporation; (c) inhomogeneous uptake of ambient Mg vapor when the Al-rich solid moves into cooler Mg gas. Region I takes up no Mg, shown as dots, so remains very Al-rich; region II takes up enough Mg to reduce  $[Al/Mg]$  to intermediate values; region III takes up so much Mg that  $[Al/Mg] \approx 1$ . (bottom) The correlation of  $^{26}Mg/^{24}Mg$  with  $[Al/Mg]$  resulting from this sequence resembles the correlation obtainable if, instead,  $^{26}Al$  had been alive *in situ* in a sample that had been able to completely homogenize the Mg isotopes prior to its decay.

observed in meteoritic samples. Whether that explanation is correct or not will be decided by chemical considerations. That is, can the observed suites of minerals conceivably be generated by a process of Mg addition to a very Al-rich precursor.

## VI. DISCUSSION

The commonly accepted interpretation that the  $^{26}Al$  was actually alive in the suite of meteoritic minerals as it is found today is adequate to describe the isotopic content of most of the data (Wasserburg and Papanastassiou 1982). It is sufficient but not necessary. So why should I go to such lengths for a different interpretation based on fossil  $^{26}Mg$ ? This interpretation offers at least four possible advantages:

1. It relieves the astrophysical requirement for a  $^{26}Al$  enhancement in the gases associated with the solar origin. These are essential data for the problem of star formation. It would be very counterproductive to assume that the data requires  $^{26}Al$  to have been alive *in situ* if that is incorrect.

2. The average  $^{26}Mg^*/Al = 0.027$  expected to reside in aluminum cores of grains is proportional to the interstellar  $^{26}Al/^{27}Al$  ratio, which I have taken to be  $0.8 \times 10^{-5}$  at the solar galactocentric radius on the basis of the distributions studied by Leising and Clayton (1985). The Max Planck balloon-borne Compton telescope has evidence that the interstellar  $^{26}Al$  is very sharply peaked toward the Galactic center (V. Schönfelder, private communication), suggesting that the nova distribution is the most likely one. If that preliminary result holds up, the ratio  $(^{26}Al/^{27}Al)_\odot = 2.25 \times 10^{-6}$  (Leising and Clayton

1985) may apply, reducing the fossil anomaly at the solar position by a factor of about 4. Because the interstellar fossil is so large, this result would present no large problem for the fossil theory, but it would be a problem for the live- $^{26}Al$  theory, considering that the interstellar  $^{26}Al$  concentration would then be almost a factor of 20 smaller than the concentration demanded by the *in situ*-decay theory.

2. Inclusions having different correlation slopes no longer have to differ in age by several million years. To require that two Allende inclusions formed  $10^7$  yr apart sets severe requirements for the accumulation of the Allende body. They can as easily differ in the initial enhancements  $[Al/Mg]_a$  of the respective Al-rich aggregates or in the degree of subsequent Mg extraction. Each solid can in this way have its own correlation slope despite essentially simultaneous formation.

3. The criterion for a fossil correlation was predicted before discovery by Clayton (1977b): "The absence of live  $^{26}Al$  would be most clearly attested to by phases having large  $[Al/Mg]$  but without large  $^{26}Mg$  excess. Comparable data on more inclusions will probably clarify this." It has done so by finding a large number of such samples, especially hibonite ( $CaO \cdot 6Al_2O_3$ ) samples. Hibonite from inclusion HAL (Lee, Russell, and Wasserburg 1979), for example, has  $[Al/Mg] \approx 10^3$  (i.e.,  $[Al/Mg] = 10^4$ ) but no detectable excess  $^{26}Mg$ ! This is no problem for a fossil correlation, which can be removed entirely by initially extracting all Mg.

4. Very  $^{26}Mg$ -rich magnesium can even exist in samples that are not extremely Al-rich. The limiting case is to take a



large- $[\text{Al}/\text{Mg}]_a$  aggregate, in which  $^{26}\text{Mg}^*/\text{Al} = 0.027$  can be achieved, and then to dilute it with normal Mg. For example, consider an aggregate that had initially  $(\text{Al}/\text{Mg})_a = 1$  (that is  $[\text{Al}/\text{Mg}]_a = 12.5$ ) before Mg was extracted to prepare a richness  $(\text{Al}/\text{Mg})_0 = 20$ . It would still have an 11% excess of  $^{26}\text{Mg}$  even after taking up ambient Mg until  $\text{Al}/\text{Mg} = 10$ . Such a scenario might account for the bizarre Leoville hibonite L-4 (Lorin and Christophe Michel-Levy 1978).

The viability of this interpretation rests not on the isotopic data, which it reproduces, but on chemical questions concerning the formation of the suites of contiguous minerals. Because the inclusion's penultimate stage is here envisioned as a uniformly  $^{26}\text{Mg}$ -rich Al-rich residue, the most Mg-rich minerals within the suite are required to have become so by the uptake of ambient normal Mg. For example, the melilite is required to have formed by the addition of Mg to those portions of the Al-rich residue that would otherwise solidify to anorthite, rather than the other way round. Even the Al/Mg variability within an apparently single anorthite crystal is required in this picture to be a memory of variable ambient Mg availability during solidification rather than a zoning phenomenon during crystallization. It is not known if such chemical histories are possible. Otherwise the construction of a fossil theory must fall back on the charmed  $^{26}\text{Mg}$ -Al correlation advanced in previous versions (Clayton 1977*b*, 1982*a*) of the fossil theory when the interstellar  $^{26}\text{Al}$  concentration today had not yet been shown by gamma-ray astronomy to be so large.

An interesting variation on the scenario described above is the simultaneous aggregation of very Al-rich grains in a hot medium with ambient Mg vapor as the grains move toward cooler regions. The very Al-rich aggregate may then contain microscopically variable Mg concentration, a "dirty snowball" model in which  $^{26}\text{Mg}/^{24}\text{Mg}$  variations with Al/Mg could be spatially preserved across the snowball if it cools more

rapidly than Mg can diffuse. Such a process is shown schematically in Figure 3. This scenario may be applicable to the hibonite crystal showing severe local correlated fluctuations in both ratios (Hinton and Bischoff 1984). Hibonite ( $\text{CaAl}_{12}\text{O}_{19}$ ) is stable against evaporation at very high temperatures and could perhaps have been sintered at high temperature from microscopic evaporative residues rich in  $\text{Al}_2\text{O}_3$  and CaO, as evaporative residues are expected to be. Such small particles turbulently aggregating together in hot MgO-rich vapor might establish a rapidly cooling hibonite crystal in which the variable Mg concentration is spatially preserved. Otherwise one must understand how zoning during cooling could establish such large inhomogeneity (a factor  $10^2$  in small-scale Al/Mg variations) as the one observed by Hinton and Bischoff. These microscopic fluctuations in the Al/Mg abundance ratio have not been explained.

The demonstration presented here shows that it is not necessary to regard the  $^{26}\text{Al}$  decays that have produced  $^{26}\text{Mg}^*$  excesses as having happened in the meteorites rather than in Al-rich solid precursors to them. It can be stated with confidence that much more  $^{26}\text{Al}$  has decayed in interstellar dust (per gram) than in meteorites (per gram). If the daughter  $^{26}\text{Mg}^*$  anomaly can successfully be interpreted in this way, the origin of the Sun can have been more serene, more typical of average cloud matter. The question may be given a Copernican flavor: if one looks out to an average low-mass star forming in a dense galactic cloud without benefit of causative dynamics from adjacent  $^{26}\text{Al}$  ejecting events, will Al-rich inclusions also exist in their meteorite parent bodies and will they also contain excess  $^{26}\text{Mg}$ ?

Finally I note to dispel confusion that exists over the following point that the demonstration given here is not really in conflict with the arguments presented by Lee, Papanastassiou, and Wasserburg (1977), even though they did conclude that the

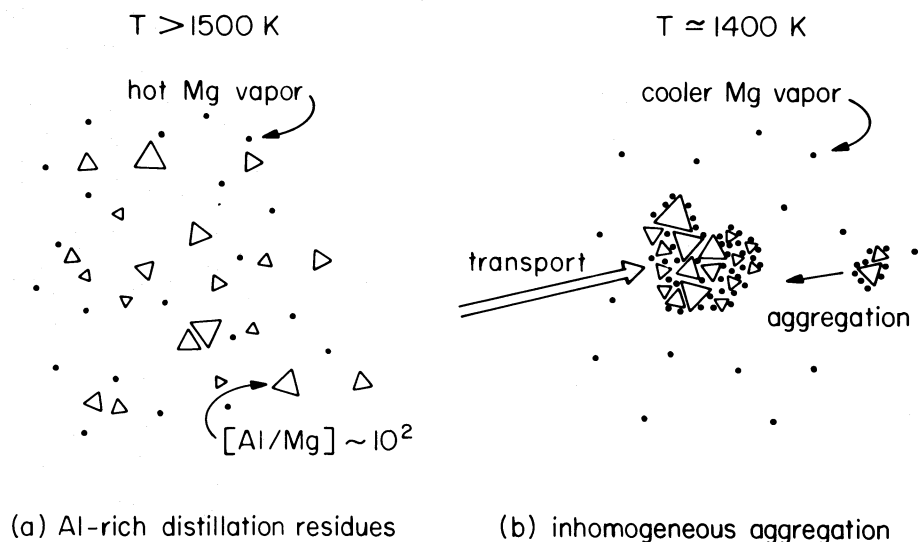


FIG. 3.—"Dirty snowball" variation of Fig. 2: (a) Many Al-rich dust particles are turbulently suspended in hot Mg vapor; the temperature  $T > 1500$  K to vaporize Mg silicates but  $T < 1700$  K to preserve  $\text{Al}_2\text{O}_3$  and, perhaps,  $\text{MgAl}_2\text{O}_4$ , both of which retain most of initial  $^{26}\text{Mg}^* = 0.027$  Al. (b) During transport to cooler Mg vapor, Al-rich particles quickly aggregate while Mg is bonding to their surfaces to trap spatial variations in Al/Mg. A gradient in Al grain sizes coated with surficial Mg could accomplish this. If this composite particle crystallizes faster than large-scale Mg diffusion, the linear correlation of Fig. 2 is generated point by point by the spatial inhomogeneity.

$^{26}\text{Al}$  was alive *in situ*. What I have produced is a more plausible form for the end members of mixing line between Al-rich  $^{26}\text{Mg}$ -rich solids at one end with solar magnesium free of aluminum at the other end. In addition to identifying a scenario for the mixing systematics called for by their analysis, I have also shown that the size of the required fossil is more than

adequate. How fascinating that the first astronomical detection of nuclear gamma rays should carry this message.

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DONALD D. CLAYTON: Department of Space Physics and Astronomy, Rice University, Houston TX 77251-1892