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A NEW INTERPRETATION OF ^{26}Al IN METEORITIC INCLUSIONS

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ABSTRACT

We suggest that the large ^{26}Al/^{27}Al $= 5 \times 10^{-5}$ abundance ratio found in calcium-aluminum–rich inclusions (CAIs) in meteorites is produced by energetic particle irradiation in the early solar system but only in a thin (0.2 g cm^{-2}) skin of the solar preplanetary disk that stops the energetic particles. Buildup of that ^{26}Al concentration happens only during the quiescent, or passive, phase of the solar disk, after accretion and associated turbulence has ceased. We propose that CAIs also originate in the form of fine Al-rich dust within a coronal-type environment atop the disk. In this model only the CAIs among planetary materials would contain this high ^{26}Al/^{27}Al ratio. Chronological ordering based on ^{26}Al content within planetary materials would be invalid in this model, which would allow chondrules of ordinary chondrites to be as old as CAIs despite their lack of ^{26}Al. This temporal reordering could resolve a growing crisis in planetary disk physics. We also outline other problems in planetary history that will be alleviated or reinterpreted if our model is correct. We describe four sources for the energetic particles, noting that for each the power requirements are reduced to credible values by the smallness of the irradiated mass, about $10^{-5}\ M_\odot$ of disk matter.

Subject headings: meteors, meteoroids — nuclear reactions, nucleosynthesis, abundances — stars: formation — Sun: flares

1. INTRODUCTION

The presence of excess ^{26}Mg in meteoritic samples correlated with the Al content of the samples provides the evidence that ^{26}Al ($t_{1/2} = 0.70$ Myr) was alive in the solar system when the samples formed. There have been two difficulties with this conclusion. The first is that the abundance ^{26}Al/^{27}Al $= 5 \times 10^{-5}$ is so large that it has proved hard to understand how a molecular cloud core can have contained such a large abundance. The present interstellar medium contains much less on average, as measured by gamma astronomy (Mahoney et al. 1984; Clayton 1984; Share et al. 1985; Diehl et al. 1993, 1995) near 3×10^{-6}, and the concentration in molecular clouds should be still much less (Clayton 1983, 1984; Clayton, Hartmann, & Leising 1993) unless the ^{26}Al was either created in the molecular clouds or injected into them from stellar nucleosynthesis events. The second difficulty is that not all early samples in meteorites seemed to have contained ^{26}Al, so that it is commonly concluded either that those samples did not solidify until millions of years later or that the ^{26}Al was inhomogeneously distributed in space. The data on the distribution of ^{26}Al in meteoritic samples are reviewed by MacPherson, Davis, & Zinner (1995), and we here repeat only a few key points needed to establish possible connections to the new model that we will present.

The large abundance ^{26}Al/^{27}Al $= 5 \times 10^{-5}$ is found only in Al-rich solids that are so large that it is believed that they can have been assembled only in the solar system disk. These objects are the so-called calcium-aluminum-rich inclusions (CAIs), millimeter-sized assemblies of texturally and petrographically related Al-rich minerals (MacPherson, Wark, & Armstrong 1988) or apparently related large (10–100 μm) crystals of hibonite or corundum (both nearly Al_2O_3 by composition). Other objects that might otherwise be believed to have formed equally early, including the chondrules that are so ubiquitous in the ordinary primitive meteorites and a class of CAIs recognized by their isotopic anomalies in stable elements, do not seem to have contained much ^{26}Al when they solidified. Was there a long time delay between the solidification of objects containing these two concentration levels of ^{26}Al? That interpretation raises a problem for disk physics, although it does not explicitly disagree with other chronological evidence. One chondrule expert (Wood 1995a, b) has argued that the chondrules should have been made in the early energetic accretion phase in the solar accretion disk in order that the disk be energetically capable of transforming up to half the mass of silicate dust into chondrules; however, the paucity of ^{26}Al in the chondrules (Hutcheon, Huss, & Wasserburg 1994; Hutcheon & Jones 1995; MacPherson et al. 1995) seems, if given that chronological interpretation, to require chondrule formation to be delayed until several Myr after the CAIs—a serious constraint on disk evolution.

2. THE PUZZLE OF THE CAIs

This problem focuses on the CAIs. Among solar system solids only CAIs show evidence of widespread ^{26}Al at the time of their formation, and their initial ^{26}Al/^{27}Al ratios are spread between 0 and 8×10^{-5}, with the largest concentration (about 40%) in their histogram falling (MacPherson et al. 1995, Fig. 1) between 4 and 5×10^{-5}, about 30% near zero, with 30% distributed between 1 and 4×10^{-5}. Although this spread is normally attributed either to different formation times for CAIs or to partial Mg-isotope reequilibration at low temperatures, the model we present will attribute it in part also to the gradual buildup owing to cosmic rays of ^{26}Al in the skin of a late quiescent accretion disk. Those minority FUN CAIs (only a few percent; MacPherson et al. 1995) having mass-dependent fractionated isotopes and nuclear isotopic anomalies, suggesting that they are very primitive, appear to have contained only very little initial ^{26}Al, although they are otherwise identical and are found close to the ^{26}Al-bearing CAIs in the meteorite. There is quite a robust anticorrelation between ^{26}Al in CAIs and in hibonite and the isotopic anomalies in the same bodies (Clayton et al. 1988; MacPherson et al. 1995). Fahey et al. (1987) showed that the rim of a Type A CAI contained more ^{26}Al than its core, inconsistent with chronological interpretation. These facts have suggested a heterogeneous spatial distribution of ^{26}Al.

Our model addresses these problems. But the origin of the CAIs, the only known bodies containing large ^{26}Al, is itself unknown. What seems required on chemical grounds (e.g., MacPherson et al. 1988) is some type of intense heating capable of driving off less refractory elements from the initial dust and leaving residues enriched in Ca, Al, Ti, and their oxides as well as in refractory trace elements, enriching them some 20-fold with respect to Mg and Si, followed by hot aggregation into millimeter-sized aggregates, followed in some cases (Type B CAIs) by melting and resolidification. What our model seeks is a good physical reason for those objects formed in some such (simplified) manner to also be the only objects that contain abundant ^{26}Al. If other objects (e.g., chondrules) form in other places not containing ^{26}Al, they may be formed at the same time or even earlier, despite their lack of ^{26}Al. Our model concentrates on the first stage of CAI cosmogony, the establishment of a medium containing fine Al-rich dust rich in ^{26}Al. It also suggests that that fine dust may aggregate into larger collections transformable to CAIs when subsequently reheated, perhaps similarly to the process (also unknown) that heated and formed the chondrules (e.g., Wood 1995a, b).

3. COSMIC-RAY–IRRADIATED QUIESCENT DISK

Our model depends on an intense irradiation of the accretion disk by cosmic rays. Nuclear reactions in the top layers of that disk create ^{26}Al there, and the local heating leading to the Al-rich dust precursor of CAIs also occurs there. The bulk of the accretion disk is shielded from both the cosmic rays and the heating mechanism and therefore generates neither abundant ^{26}Al nor large Al-rich aggregates. CAI-progenitor aggregates gathered in the top layers sink (sediment) toward the central plane, where they are incorporated with other less refractory solids into the meteorite regoliths. This can occur only during a quiescent phase (Shu, Adams, & Lizano 1987; Cameron 1995) of the solar disk, when accretion onto the Sun has stopped, when disk turbulence has stopped, so that the upper irradiated layers maintain their material identity during the period (perhaps 10^5–10^6 yr) while the ^{26}Al abundance builds up there and while the less refractory elements are driven off, plausibly convected away by surface flows. Note that the ^{26}Al abundance grows temporally (rather than decays!) in the surface skin after convective mixing has stopped, giving possible interpretation to the CAI spread of ^{26}Al/^{27}Al ratios between 0 and 5×10^{-5}, suggesting that a large fraction of the CAIs were formed after the buildup of ^{26}Al was complete. The CaAl-rich residues are aggregated by mutual collisions (caused perhaps by surface waves) and sink. Near the midplane, where chondrule and CAI heating may occur, the only CaAl-rich objects are the ones that had this history; they are therefore also the only ones that contain such abundant ^{26}Al. The other planetary bodies do not, on this picture, contain comparable ^{26}Al, nor does the Sun itself, so it is less likely in this model that ^{26}Al was a significant heat source for the melting of differentiated planets.

For the quiet disk we use the minimum-mass solar nebula of Hayashi (1981), derived from the mass and morphology of our present solar system. A visualization in Figure 1 shows the inner AU or so of a flaring disk with dust having begun to sediment in the outer part, following Miyake & Nakagawa (1995), who give a very full description of the situation and its rationale. We require that the disk be stably stratified until such time that, for whatever reason, the large dust (CAIs) sinks, picking up other small pieces first and then other less refractory matter as it goes. This affords a way for the very refractory CAIs to contain by subsequent alteration (e.g., MacPherson et al. 1988) a large abundance of more volatile elements (e.g., Na, K, and Fe).

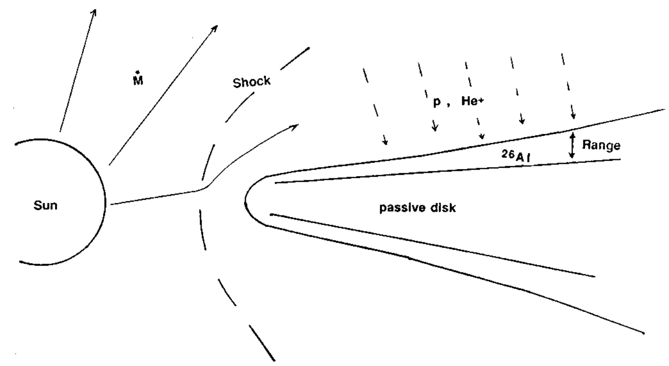

FIG. 1.—Salient features of the proposed setting, showing the central AU. The disk accretion and accretion onto the central Sun has stopped (a passive disk). The T Tauri Sun now has a wind rather than a bipolar outflow, amounting to 10^{-7} to 10^{-6} $M_\odot$ yr^{-1} from the Sun. Energetic protons and alpha particles (tens of MeV nucleon^{-1}) strike the disk surface and are stopped within their range. The ^{26}Al is produced within that skin depth and builds up only there. The CAIs also form in that skin and thus contain ^{26}Al. The energetic particles may come from the Sun (solar flares), the disk (disk flares), the bow shock, or the termination shocks (not shown) for the wind.

The cosmic rays called for may be emitted by solar flares, or they may be "anomalous cosmic rays" similar to those known in the solar system today (Mewaldt, Spalding, & Stone 1984; Mewaldt et al. 1993). The latter are singly ionized (Klecker et al. 1995) ions of 5–30 MeV nucleon^{-1} that have been produced in the solar wind (Fisk, Kozlovsky, & Ramaty 1974). We focus on either proton, He^+, or $^{16}O^+$ ions as the active cosmic rays for ^{26}Al production. Figure 1 sketches a dashed bow shock between supersonic T Tauri wind and the inner disk. Neutral He from the inner disk will diffuse into this shock, be ionized, be picked up, and be accelerated at the shock just as in today's anomalous cosmic rays, but with vastly greater flux. And flares may occur on the disk if magnetic reconnection happens there (e.g., Cameron 1995), and their proximity may render the particle fluence quite substantial in the disk skin. Numerous irradiation effects are well known in meteorites (see Caffee et al. 1988); however, these records are of later events than the very early scenario that we describe.

The surface density for the minimum-mass nebula (Hayashi 1981) is $\Sigma(r) = 1.7 \times 10^3\ (r/1\ \mathrm{AU})^{3/2}$ g cm^{-2}, about 200–350 g cm^{-2} in the asteroid region. This thickness far exceeds the range of cosmic rays near 20 MeV nucleon^{-1}. If the nebula is for the moment taken to have solar composition (no dust/gas enhancement) the range of 20 MeV nucleon^{-1} particles is about 0.23 g cm^{-2}, only about 0.1% of the disk thickness. It varies with energy as $R = (0.23\ \mathrm{g\ cm^{-2}}) \times (E/20\ \mathrm{MeV\ nucleon^{-1}})^{1.84}$ (Clayton & Jin 1995). This restricts ^{26}Al production to about 10^{-3} of the total disk mass (which is itself about 0.02 $M_\odot$ between 0.1 AU and 100 AU). So 20 MeV nucleon^{-1} alpha particles would need create ^{26}Al only within 2×10^{-5} $M_\odot$ of disk skin rather than throughout, greatly reducing the power

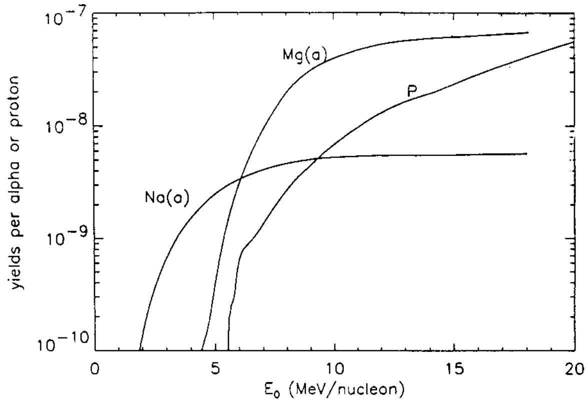

FIG. 2.—The number of ^{26}Al nuclei created by a stopping proton or alpha particle (the yield). The initial energy (MeV nucleon^{-1}) is E_0. This calculation (Clayton & Jin 1995) integrates the reaction cross section over the particle's deceleration path. Either particle stops with total range $R = 0.23$ g cm^{-2} (E_0/20 MeV nucleon^{-1})$^{1.84}$.

needs from those of previous estimates (Clayton, Dwek, & Woosley 1977; Clayton & Jin 1995). The major reactions producing ^{26}Al are ^{26}Mg(p, n)^{26}Al, ^{27}Al($p, p'n$)^{26}Al, and ^{28}Si($p, p'pn$)^{26}Al for protons and ^{23}Na(a, n)^{26}Al and ^{24}Mg(a, pn)^{26}Al for alphas. Oxygen ions also effectively produce via ^{12}C(^{16}O, pn)^{26}Al, and because $^{16}O^+$ has the largest overabundance in today's anomalous cosmic rays, they must also be regarded as contenders in the early solar system for the ^{26}Al-producing ion (Clayton & Jin 1995). The yield (number of ^{26}Al nuclei produced per stopping particle) is obtained by integrating the production cross section along the stopping path of the particle while it slows by ionization processes. Clayton & Jin (1995) have performed these integrals. Figure 2 shows the ^{26}Al yield for both protons and alphas as a function of their initial energy, as computed for solar gas. If dust enhancement occurs in the disk, these yields would go up, because the ^{26}Al production utilizes collisions with Mg and Si and, for $^{16}O^+$, with ^{12}C.

Consider the example of alpha particles at 20 MeV nucleon^{-1}. Figure 2 shows the yield, primarily from ^{24}Mg targets, to be 8×10^{-8} ^{26}Al nuclei per stopped alpha particle. To establish the ratio ^{26}Al/^{27}Al = 5×10^{-5} in 10^{-5} $M_\odot$ of disk requires production of 1.3×10^{42} ^{26}Al nuclei, and from the yield, that requires 1.6×10^{49} alpha particles stopped in the skin. This is about 3% of the initial number of He in 10^{-5} $M_\odot$ skin. At 20 MeV nucleon^{-1} the total energy of the alphas is 2×10^{45} ergs. If this were delivered over 10^6 yr the surface flux would be 6×10^6 cm^{-2} s^{-1} and required power for irradiating a disk surface area 10^3 AU^2 would be 1.6×10^{32} ergs s^{-1}, a few percent of the solar luminosity. If the T Tauri wind is 10^{-7} $M_\odot$ yr^{-1} (Bertout 1989), the associated mechanical power would be about 3×10^{32} ergs s^{-1}, barely adequate for the needed anomalous cosmic-ray acceleration, given a sufficient rate of drift of neutral He into the ionizing region. We conclude that the power needs may be available, even though just barely, a big improvement on the 1000 times greater power requirements envisioned in earlier treatments (Clayton et al. 1977). The required cosmic-ray flux is 10^9 times greater than that of the anomalous CR today; however, today the solar wind is 10^7 times smaller, and there is very little ambient He to drift into it owing to our very small local circumsolar interstellar density. Putting this much power into solar cosmic rays is also a daunting challenge. These power requirements would be lessened by enhancement of the dust-to-gas ratio in the disk surface. Although power requirements of the model stretch credulity, it is humbling to realize the ^{26}Al/^{27}Al = 5×10^{-5} is so large that *all models stretch credulity*. It remains one of the great puzzles of astrophysics.

4. DISCUSSION

Perhaps the biggest shortcoming of this new model is that we cannot give a full description, long sought, of the origin of the CAIs. However, this shortcoming plagues every model. Our model can be viewed as the specific suggestion that the CAI Al-rich precursors containing ^{26}Al form in the skin layer of the quiescent solar disk rather than throughout that disk or in its midplane. This places their formation late in the evolution of the solar disk, whereas they have commonly been thought to be early owing to their ^{26}Al content. If the CAIs, or at least their Al-rich dust precursors, do form in that skin, their ^{26}Al content and the lack of it elsewhere can be interpreted by our model. The missing ingredient is the heating capable of driving off the less refractory solids to leave Al-rich residues. Thermally this requires dust temperatures of about 1700 K, and the particle flux, though dramatic, is not sufficient to maintain such temperatures. Dust may cool in seconds of free radiation to the vacuum. But this does not preclude the particle irradiation from responsibility for the Al richness because evaporation from activated small particles may also occur within seconds. We mention five possibilities: (1) Intense and frequent thermal spikes in the fine-grained dust precursors to CAIs may be able to drive off less refractory solids even though the time-averaged temperature is only a few hundred kelvins. The lower energy secondaries deposit more energy in small grains than do energetic primaries. (2) Sputtering may preferentially enrich Al/Mg in the particles. The sputtering spikes may preferentially eject those particles less chemically attached to the mineralizing structure, while at the same time their energy cascades may promote annealing. If the atoms made gaseous continuously "boil away" or are advected away by surface breezes from the disk skin, a residual skin enriched in Al dust may facilitate the growth of Al-rich solids over perhaps 10^6 yr of available time. (3) Because the skin is ionized, whereas the interior disk is nearly cold and neutral, the skin may be more subject to ohmic heating. (4) Cameron (1995) described how disk flares may result from the solar wind in phase 4 episodically embedding magnetic field in the disk, and those flares may not only heat the surface dust but may even provide the primary energetic particles. The flares may even provide the heating by UV continuum. (5) The best source may be mechanical heating unrelated to the energetic particles but very much related to the surface skin location. MHD waves in that surface may steepen abundantly into shocks, making a coronal environment much hotter than the interior. Although the Al-rich dust may be heated by hot electrons, it is perhaps more likely that they are heated by the frictional drag attendant to their higher inertia. When a shock passes, the grain suddenly moves at high speed with respect to the gas and is heated like a meteor (Hood & Horanyi 1993; Ruzmaikina & Ip 1994). Al-rich dust cannot exist in today's solar corona, not because of the high coronal temperature but because of the intense solar luminosity; but we envision that question in the analogous case of the mechanically overheated corona in the absence of solar luminosity.

This work bears a resemblance to earlier (Clayton et al.

1977) treatment of solar system irradiation and to very modern investigations of ^{26}Al production within molecular clouds by their cosmic-ray irradiation (Clayton 1994; Clayton & Jin 1995; Ramaty, Kozlovsky, & Lingenfelter 1996), which has been revealed by gamma-ray lines detected by *Compton Gamma Ray Observatory* (Bloemen et al. 1994). Indeed, those efforts stimulated much of our thinking. But the differences are profound. Those papers interpreted the ^{26}Al as being produced uniformly in disk and cloud core. We now suggest that the ^{26}Al is inhomogeneously located in a small fraction of the disk mass. The natural inhomogeneity of the ^{26}Al in our model suggests solutions to many of the problems associated with the assumption of homogeneous ^{26}Al. In this aspect we have been motivated also by studies suggesting Al inhomogeneity from the meteoritic evidence (MacPherson et al. 1995; Hutcheon et al. 1994; Hutcheon & Jones 1995). The recent reformulation of the supernova trigger for admixing supernova debris into the solar nebula (Cameron et al. 1995) also envisions homogeneous ^{26}Al concentration.

Every irradiation model for producing ^{26}Al faces the threats of overproducing both ^{53}Mn and ^{9}Be (Clayton & Jin 1995). The present model defeats this problem because the ^{53}Mn and ^{9}Be may be too volatile for proportional incorporation into the CAIs, which by their very nature have lost all but the most refractory of elements. Those ^{53}Mn and ^{9}Be atoms mostly evaporate from the disk surface in our picture, and they were made nowhere else. But the very short lived and much more refractory ^{41}Ca (Srinivasan, Ulyanov, & Goswami 1994) is amply produced (Clayton & Jin 1995; Ramaty et al. 1996) and is, of course, incorporated into the Ca-rich CAIs at the very location at which they were irradiated and formed. Ramaty et al. (1996) calculate that the ^{41}Ca may even be 10-fold overproduced relative to ^{26}Al (although in a different setting and different irradiation). But temporal delay between the surface production of the ^{26}Al-^{41}Ca–rich refractory dust and the subsequent formation from it of the CAIs by chondrule-forming heating events in the disk interior may easily reduce the ^{41}Ca to the observed level. Moreover, although the ^{53}Mn production in our model will probably be enhanced by roughly a factor of 10 in the bulk skin (depending on the fast particle composition and energy), condensation of even a fraction of it along with the refractory elements offers the possibility of understanding why ^{53}Mn/^{55}Mn measured in CAIs ($2.4–9 \times 10^{-5}$; Birck & Allegre 1985) is up to 10 times greater than the initial ^{53}Mn/^{55}Mn ratio (8×10^{-6}) inferred from angrite meteorites (Lugmair, MacIsaac, & Shokulyukov 1992). This great difference would thus not bear chronological significance in our model, releasing that constraint also. Lack of excess ^{6}Li may be a problem for the CAIs if they have normal Li isotopes (Phinney, Whitehead, & Anderson 1979) and if they were in the initial condensate with the Al rather than a later alteration product.

Some particle-irradiation nuclear products may have been mixed throughout the disk if the cosmic-ray irradiation was active during earlier disk phases, while turbulence was still widespread. Contributions to ^{53}Mn, ^{9}Be, and ^{11}B, as well as a smaller concentration of ^{26}Al than the value found in CAIs, may pervade the inner disk by this process. Examples could be the smaller ^{26}Al concentration found in the chondrules (Hutcheon et al. 1994; Hutcheon & Jones 1995) and the ^{11}B isotopic variations in chondrules found recently by Chaussidon & Robert (1995). But despite these interesting speculations, we repeat that the dominant motivation for our new picture is its potential for clarifying why large ^{26}Al concentrations appear only in that small fraction of disk matter from which the CAIs also form.

Requiring the surface gram per cm^{-2} to retain its identity for up to 10^{6} yr may appear unreasonable, but it may be reasonable owing to the temperature inversion. Surface gas is kept hotter than disk gas by mechanical-wave dissipation (as in coronae). We are also attracted to the idea that gas atoms are continuously lost from the disk surface, whereas Al-rich dust particles, or aggregates thereof, are retained because their scale height is less. The surface solar wind occurring in Cameron's (1995) phase 4 may pick up the hot ions atop the skin. This might allow the elemental Al concentration to build up during 10^{6} yr of energetic-particle irradiation. The gradual growth of Al-rich solids would be facilitated by this. The disk must be in its passive state, without turbulence, for all of this to occur. Cameron (1995) associates this phase 4 with the weak-line T Tauri phase, after the stopping of accretion. The skin Al-rich solids contain abundant ^{26}Al, whereas disk Al does not. In the last phases of the passive disk, these solids precipitate increasingly rapidly toward the midplane (Miyake & Nakagawa 1995), gaining more volatile trace elements (e.g., Na, K, and Fe) whose presence is in CAIs is problematical (MacPherson et al. 1988) if interpreted by thermal condensation and eventually being swept up with fine-grained matrix into the meteorite regolith where they are found. The chondrules may have been formed at the same time or even earlier but without appreciable ^{26}Al content because they formed from normal bulk dust precursors rather than from Al-rich precursors.

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