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GAMMA RAYS, COSMIC RAYS, AND EXTINGUISHED RADIOACTIVITY IN MOLECULAR CLOUDS

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ABSTRACT

We investigate causal connection between two astonishingly big numbers: the very large ^{26}Al concentration (5×10^{-5} of ^{27}Al) in the early solar system and the very large nuclear excitation rate in Orion clouds. We present three separate pictures attributing ^{26}Al within the early solar system and other molecular cloud cores to special cosmic-ray irradiation of those cloud cores. These pictures reinterpret the large $^{26}\text{Al}/^{27}\text{Al}$ ratio found in the early solar accretion disk, and seem not to be relevant to the present interstellar $1.5 M_{\odot}$ of ^{26}Al . These three pictures of cosmic-ray irradiation of molecular clouds accounting for their high ^{26}Al content are:

1. High flux of low-energy cosmic ray O, Na, Mg, and Si nuclei stopping in the clouds with partial conversion to ^{26}Al by nuclear interactions while they stop (Clayton 1994);
2. Stopping of low-energy galactic cosmic rays, which are known (at 100 MeV nucleon $^{-1}$) to carry the very large activity $^{26}\text{Al}/^{27}\text{Al} = 0.1$ and which we argue to be absorbed by cloud cores;
3. Stopping of newly synthesized particles accelerated from local ejecta of supernovae and W-R star winds, which carry activities as great as $^{26}\text{Al}/^{27}\text{Al} = 0.01$ from those events.

In these pictures the cosmic rays may be very different in origin than the galactic cosmic rays. At low energy they are injected into clouds and stopped in the cloud cores. We normalize our expectations for massive clouds to the inelastic nuclear excitation rates of $^{12}\text{C}^*(4.43 \text{ MeV})$ and $^{16}\text{O}^*(6.13 \text{ MeV})$ gamma rays emerging from the clouds in Orion (Bloemen et al. 1994). Picture 1 is plagued by very large power requirements if the accelerated particles are predominantly hydrogen. Nonetheless, we show that several other extinct radioactivity concentrations that accompanied ^{26}Al in the early solar system would be coproduced by ordinary cosmic-ray composition. Our most promising construction of picture 1 appears to be anomalous acceleration of ^{16}O ions (as known from the solar wind) to several MeV nucleon $^{-1}$, resulting in both 4.43 and 6.13 MeV gamma ray lines and $^{12}\text{C}(^{16}\text{O}, pn)^{26}\text{Al}$ in the clouds. Those ions ease the risk of producing too much ^{53}Mn , which plagues each picture unless proton bombardment is suppressed by the acceleration mechanism. We confirm that overabundance of ^9Be in solar matter also plagues irradiations producing ^{26}Al within it unless those energies are less than about 10 MeV nucleon $^{-1}$.

We motivate each of these pictures by advancing a magnetized raisin-pudding model of molecular clouds and their embedded cores. The model suggests that both the nuclear interactions and the stopping of the ions occur preferentially within the dense cores of molecular clouds, which causes those cores to accumulate larger $^{26}\text{Al}/^{27}\text{Al}$ ratios than does the bulk of the molecular clouds. We argue that cosmic rays from OB associations drive the turbulence within molecular clouds near them. It is possible that these processes, rather than fresh radioactivity ejected from stars, cause star-forming regions to contain several of the extinct radioactivities near levels found in the early solar system. A new chapter in the relationship of OB associations and cosmic rays to the origins of solar systems has been opened by the COMPTEL detection.

Subject headings: cosmic rays — gamma rays: theory — ISM: clouds — nuclear reactions, nucleosynthesis, abundances — solar system: general

1. INTRODUCTION

The Compton telescope (COMPTEL) team (Bloemen et al. 1994) on NASA's *Compton Gamma Ray Observatory* has recently reported gamma radiation from the Orion cloud complex in the 3–7 MeV range that appears to be a superposition of the 4.43 MeV de-excitation line from $^{12}\text{C}^*$ and the 6.13 MeV de-excitation line from $^{16}\text{O}^*$. The excitations are proposed by them to happen when heavy cosmic rays interact with ambient H and He in the molecular clouds. The observed flux sum near $1 \times 10^4 \text{ cm}^{-2} \text{ s}^{-1}$ in these two lines is at least one order of magnitude greater than one expects from cosmic-ray interactions based on the cosmic-ray flux observed in the solar system near 1 GeV per nucleon, requiring some form of cosmic-ray enhancement in these clouds. This startling observation has prompted a major rethinking of two important problems: the existence of ^{26}Al in molecular clouds and the

constancy of cosmic rays in time and space. There exists about $1.5 M_{\odot}$ of ^{26}Al that gamma astronomy has found to pervade the interstellar medium (Share et al. 1985; Diehl et al. 1993, 1994), but that mass endows the interstellar medium (ISM) with an average aluminum isotopic ratio near 3×10^{-6} , not nearly enough to account for the puzzling ratio $^{26}\text{Al}/^{27}\text{Al} = 5 \times 10^{-5}$ found within meteoritic inclusions formed in the early solar system. Recent review of all aspects of ^{26}Al nucleosynthesis and its mean distribution throughout the ISM has been provided by Prantzos & Diehl (1995). Understanding even the smaller interstellar isotopic ratio 3×10^{-6} found there on average has presented astrophysical challenges (Clayton 1984; Clayton, Hartmann, & Leising 1993; Timmes, Woosley, & Weaver 1995). The discovery by Gray & Compston (1974) of live ^{26}Al in the solar system was a pivotal one for problems associated with solar birth and its relationship to

star formation generally. The correlation of excess ^{26}Mg with Al/Mg abundance ratio was demonstrated more completely by Lee, Papanastassiou, & Wasserburg (1977), who argued that the parent ^{26}Al had to have been alive when the Ca-Al-rich inclusions formed. The question of the “liveness” of the ^{26}Al in the actual inclusions as they solidified was repeatedly questioned: first by a “charmed-carrier model” of fossil $^{26}\text{Mg}^*$ in aluminum (Clayton 1977a, b; 1982), a process that had been predicted to be of measurable importance (Clayton 1975) for meteoritic samples; subsequently by a chemical vapor-fractionation scheme for preparing fossil-rich parents of CAI constituents (Clayton 1986) in the solar accretion disk from fossil-rich interstellar aluminum. As challenging as fossil effects may emerge to be as knowledge of the chemical history of matter improves, in this work we will eschew such interpretations. They are too controversial. We address specifically the bewildering lengths to which interpretations of live ^{26}Al must go to fit into an integrated astrophysical picture.

Clayton (1994) argued that the puzzling large abundance of ^{26}Al in our solar system may reflect a similar cosmic radiation phenomenon to that now observed in Orion. If the Sun was born in a molecular cloud core near an interface with a new O association, it may now, without special pleading, be regarded to have also been irradiated with a high flux of low- E cosmic rays. The COMPTEL observations attest to $2 \times 10^{39} \text{ s}^{-1}$ excitations of $^{12}\text{C}(4.43 \text{ MeV})$ nuclei in the Orion region. That rate surprised by its large size. The total mass of molecular clouds in the entire inner Galaxy is about 10^4 times that of the Orion cloud mass (about $10^5 M_\odot$), though perhaps 10–20 times more distant on average, so that if all molecular clouds were in similar condition the Galaxy would be at least 30 times brighter in integrated 4.43 MeV photons than is Orion, which would also exceed the known upper limits allowed from *SMM* measurements (Harris, Share, & Messina 1995) by more than 10-fold. In similar spirit Harris et al. (1995) showed that the total Galactic center flux from its central radian is no greater than 4.7 times the published COMPTEL flux from Orion at 4.43 MeV. They could not place useful limits on the Orion source itself, since the COMPTEL measurement was of a flux at least 3 times less than the *SMM* upper limit from Orion. Nonetheless those authors observe that if the sources are steady in time, the Orion-like sources must be less centrally located than other conventional markers of Galactic structure. If, on the other hand, molecular cloud mass is irradiated only after a large star mass has just formed from it, as Clayton (1994) suggested in the Orion case, it could bring these relative brightnesses into line and, of especial significance, could perhaps explain why the forming solar system was itself part of such an irradiation. In expressing his own doubt that the entire $2 M_\odot$ of ^{26}Al could have been produced in this way, Clayton (1994) called into question from the outset the “duty cycle” of irradiation of average cloud matter, “the fraction of total molecular-cloud mass that has been bombarded over the past 10^6 yr.” These arguments now dispel the possibility that the galactic glow at 1.809 MeV from ^{26}Al decay owes its strength to cosmic-ray production. On the galactic scale its abundance is certainly the product of galactic nucleosynthesis. But it would be quite unjustified to infer that the *extra enhancement* of ^{26}Al in the early solar system was created by the same nucleosynthesis process that created the bulk of galactic ^{26}Al . The problem with stellar nucleosynthesis has been and still is that of admixing it quickly enough into the solar cloud core. It is entirely plausible that the large ^{26}Al concentration in the early solar

system and the large mass of ^{26}Al in the galaxy today have totally unrelated sources, because they are found in apparently unrelated places. The average molecular cloud should contain virtually no ^{26}Al , considering that it decays to vanishing levels within several Myr, much shorter than the assembly time of cloud matter (Clayton 1983). The cosmic-ray pictures advanced in this work address the large isotopic ratio, $^{26}\text{Al}/^{27}\text{Al} = 5 \times 10^{-5}$, found in the early solar accretion disk. Clayton’s (1994) point was that it is impossible to have $2 \times 10^{39} \text{ s}^{-1}$ excitations of $^{12}\text{C}(4.43)$ without simultaneously producing a lot of ^{26}Al . The question is the distribution of those excitations, which we will argue to be concentrated in molecular-cloud cores.

Although some of our numerical requirements will seem of surprising magnitude, perhaps at first not even credible, we are obligated to seek a resolution of two surprisingly large numbers—the gamma flux from Orion and the ^{26}Al concentration in the early solar system. Our entire purpose is the significant question of whether these two surprises may be related, and in order to seek those possibilities we take the role of advocacy, seeking physical ideas that can accommodate their association. This gives our paper a flavor of advocacy; but by the same token, we will elucidate the problems that stand in the way.

In this work, and previously in abbreviated form (Clayton & Jin 1995; Jin & Clayton 1995), we introduce three physically distinct pictures in which cosmic-ray irradiation of molecular clouds might account for the presence of ^{26}Al in those clouds:

1. High flux of low-energy heavy ions stopping in the clouds with partial conversion to ^{26}Al by nuclear interactions while they stop;
2. The low- E tail of the galactic cosmic rays, which carry the very large activity $^{26}\text{Al}/^{27}\text{Al} = 0.1$ and which are stopped in the clouds. Recent measurement (Lukasiak et al. 1994a) of the ^{26}Al abundance in the galactic cosmic rays gives vivid evidence for that interpretation;
3. High flux of local cosmic rays accelerated from the ejecta of supernovae and W-R star winds and which carry activities as great as $^{26}\text{Al}/^{27}\text{Al} = 0.01$ from those events and which are injected and stopped in the clouds.

In our emphasis on equations of extinct radioactivity in the early solar system, this paper may be seen as an extension, prompted by the discovery of gamma rays from Orion, of earlier attempts (Fowler, Greenstein, & Hoyle 1962; Clayton, Dwek, & Woosley 1977) that considered energetic particle irradiation of the solar accretion disk. In the present paper we envision irradiation of the solar molecular-cloud core by particles accelerated by the young stellar association. But new possibilities for the irradiation of the solar disk are also raised. Consider first the problems in the way of creating an interpretation.

1.1. Problem 1: 1–3 MeV Gammas, and What Is Being Accelerated?

Ramaty, Kozlovsky, & Lingenfelter (1995) have demonstrated that the spectrum of gamma rays observed by COMPTEL from Orion can be accounted for by cosmic-ray collisions, although some restrictions are needed to avoid an observable flux of 1–3 MeV gamma rays (which Bloemen et al. 1994 only constrained with upper limits). This restriction takes the form of requiring the ratio of cosmic-ray abundances (at fixed energy nucleon $^{-1}$) $(\text{C} + \text{O})/(\text{Si-Fe})$ to be enhanced with

respect to solar (interstellar abundances), because the 1–3 MeV quanta arise from the heavier group of nuclei. This enhancement need be no more than a factor 3, however, so it is not extreme in its implication. But if it is demanded that Orion be typical of all ^{26}Al -producing irradiations, the limit to 1–3 MeV gamma rays from Orion does limit the global production of ^{26}Al over the entire ISM during the past 1.0 Myr to be no more than 5% of the observed $2 M_{\odot}$, a problem overlooked by Clayton (1994).

But the source of such cosmic rays remains a problem. What exactly is being accelerated? The ordinary galactic cosmic rays (GCRs) are totally ionized, stripped of all atomic electrons by high-velocity passage through matter (Letaw et al. 1985), which renders their propagation into increasing magnetic fields more difficult. Previous arguments for partially ionized cosmic rays have not held up (Tylka et al. 1995). Locally accelerated cosmic rays, on the other hand, are probably only moderately ionized, which aids their penetration of increased cloud magnetic fields. Thus picture 3 above and the singly charged anomalous cosmic rays that we call attention to in picture 1, § 2.3, may deal with singly ionized cosmic rays (CRs). We stress the significance of single charge on the ability to penetrate magnetic fields. Ramaty et al. (1995) called upon acceleration of the ejecta from WC stars because of their H and He deficiency, without giving cause for the acceleration to favor that rare ejecta over the acceleration of much more abundant matter. Bykov & Bloemen (1994) invoked the overabundance of oxygen in supernova ejecta for the selected particles, again without compelling reasons for the acceleration of only those particles. The argument by Nath & Biermann (1994) selecting W-R wind particles has similar problems in the selectivity of the acceleration. In § 2.3 we introduce the significance of the “anomalous cosmic rays,” as in the solar system.

1.2. Problem 2: A Physical Image of the Setting

For each of these three pictures we utilize a magnetized raisin-pudding model of the molecular clouds and their embedded cores. The mechanisms cannot be intelligently discussed without a physical picture of the setting; therefore, one of our objectives is suggesting a useful way to think of a possible setting. Although some arguments and quantities seem initially implausible, we emphasize the huge measured gamma flux from Orion as the driver for the assumptions. We will demonstrate that any CR component that enters a molecular cloud is preferentially stopped in the molecular-cloud cores. This causes those cores to be enriched relative to mean cloud mass in the nuclear products of each of the three pictures. Because the cores represent the formation sites of new stars, and by inference of our solar system, this causal connection may explain why the ^{26}Al (and other extinct radioactivities) are found in the early solar system. Those radioactivities are produced in matter that is already on the verge of collapse.

1.3. Problem 3: Large Power Dissipation in Cloud Cores

In our raisin-pudding model we also call attention to the ability of the magnetic fields to focus the CRs into those clouds. They will stop in the dense cores. That would necessarily create infrared hotspots owing to the huge power dissipation that those cores necessarily absorb in stopping the huge energy flux. The resultant large infrared luminosity, at least $10^5 L_{\odot}$, may exceed observed and theoretical limits on the luminosity and rates of ionization. Infrared hotspots are common, in Orion and elsewhere, and perhaps the common attribution of the

highly luminous hotspots in molecular clouds to gravitational contraction is incorrect. Ionization losses may be the power sources. We also remark on the capability of CR ionization losses to drive the ubiquitous but unexplained turbulence found in star-forming clouds. The very energetic molecular cloud turbulence may even be viewed as yet another surprisingly large number that we seek to unify.

Ramaty et al. (1995) also noticed this power problem. They concluded that at the very least the cosmic rays must be deficient in H and He in comparison with the GCRs in order that the observed gamma flux not be associated with huge thermal dissipation. They suggested accelerating (by an unspecified mechanism) a composition based on the specific ejecta of a WC star, which is indeed H and He deficient. Their objective was to address the observed flux of 4.43 MeV gammas; but it requires a power of $10^5 L_{\odot}$ and those authors expressed concern over such a high power demand. Our estimate to follow, based on the attempt to provide $^{26}\text{Al} = 5 \times 10^{-5} \text{ } ^{27}\text{Al}$ in 1% of the cloud ($1000 M_{\odot}$), will lead to virtually the same power requirement, even without H and He in the cosmic rays. The lack of sufficient massive star power today is a serious problem, but we will suggest below that the past power may have been stored for delivery today as cosmic rays into the clouds (§ 3.1).

1.4. Problem 4: Specific Abundance Limits

Nuclear reaction rates are unavoidably large in any region producing 2×10^{39} gamma rays s^{-1} . But the attempt to extend that production to the early solar system confronts another set of data—the solar abundances. The particles producing ^{26}Al there must not be allowed to overproduce any other known abundance in solar matter. For most elements, this is no problem; but two classes of nuclear abundance problems do exist. The first is other extinct radioactivities. The most severe limit of this type will arise from 5.3 Myr ^{53}Mn . The second class of abundance problems associated with solar system irradiation occurs for the rare light nuclei Li, Be, and B (Clayton et al. 1977). These are bypassed by stellar nucleosynthesis and their existence is attributed to CR irradiation of the ISM (e.g., Reeves 1994). There has long been a suspicion (e.g., Reeves 1994) that the ISM houses a component of low-energy CRs not detected at Earth. The evidence is the large solar $^{11}\text{B}/^{10}\text{B} = 4.0$ abundance ratio. The high-energy CRs produce the ratio $^{11}\text{B}/^{10}\text{B} = 2.5$. At low energy, however, near 10 MeV, the ^{11}B production becomes greater, so that a superposition of GCRs with a low-energy component can resolve the difference (Walker, Mathews, & Viola 1985). Very new but indirect support of this idea comes from measurements of $^{11}\text{B}/^{10}\text{B}$ in meteorites that show that ratio to have 10% variations, correlated moreover with the B/Si abundance ratio in the sample (Chaussidon & Robert 1995). Those authors attribute this variation to the low-energy irradiation of the early solar cloud. The first work to calculate light-nucleus production in the Orion context (Casse, Lehoucq, & Vangioni-Flam 1995) resolved the $^{11}\text{B}/^{10}\text{B}$ problem with just such a low-energy component. They expect of order 100 present-day “Orions” to account for the galactic abundance of B. On the other hand, one expects the most stringent limitation to lie with the rarest of those light nuclei, ^9Be .

1.5. Problem 5: Orion Now versus Solar Cloud Then

There exists a fundamental limitation to using Orion as a guide to the early solar system. Orion is *now*—one cosmic instant and place; but the early solar system was about 5 Gyr

ago, another time, place, and setting. As tempting as it may be, for sake of economy, to try to account for the solar radioactivities in today's Orion clouds, that aim may be inappropriate. The CR effects may be related without being identical. Orion is a wonderful astronomical laboratory. It contains 56 O6–B2 stars (Genzel & Stutzki 1989) and numerous examples of current star formation; its star formation history can be reconstructed (Brown, deGeus, & de Zeeuw 1994); and its plasma flows can be measured with unprecedented detail (O'Dell 1994). But its circumstances today have matured since the formation of the low-mass stars (and solar systems) that already exist there. The W-R stars and the core-collapse supernovae in Orion have already occurred (Brown et al. 1994; Blaauw 1964), and most of the star formation may be over (though some is obviously continuing today). So the infrared luminosity today may not be appropriate to earlier phases of Orion's history. On the other hand, the gamma rays are observed today. We therefore question any negation (e.g., Ramaty et al. 1995) of our ideas that is based on a setting, composition, and energy spectrum required to simultaneously account for Orion's gammas at 4.43 and 6.13 MeV while it produces $^{26}\text{Al} = 5 \times 10^{-5} \text{ }^{27}\text{Al}$. Such an achievement might be compelling support for our suggestion, but lack of such agreement does not rule it out. We advance also low-energy fluences that would not produce the gamma rays in Orion today. If the Orion gammas are seen as requiring large flux of 20 MeV nucleon $^{-1}$ oxygen ions, for example, that indirectly also increases the likelihood that the solar cloud core may have been irradiated with large flux of 2–3 MeV nucleon $^{-1}$ alpha particles. We seek internal systematics that can clarify that ambiguity.

Finally we state that it is not our presumption to solve the aforementioned problems. Their statement is to clarify our task. Our purpose is to present physical scenarios that may accommodate the suspected relationship between gamma rays and ^{26}Al . We strive to remedy the absence of physical scenarios in other works. The reader may view our effort as a search for requirements that could allow the suspected relationship to exist.

2. TRANSMUTATION OF STOPPING HEAVY IONS

The COMPTTEL discoverers of 4.43 MeV gammas (Bloemen et al. 1994) argued that excitation probability was higher for ^{12}C and ^{16}O CRs striking interstellar atoms than for H and He CRs striking interstellar ^{12}C and ^{16}O , because the ratio $(\text{C} + \text{O})/\text{H}$ is larger in CRs than in the ISM. By the same token reactions will produce ^{26}Al from O, Na, Mg, and Si in the CRs. Not only is O/H enhanced in the usual galactic cosmic radiation, but the Mg/O is also enhanced by another factor 3 (Mewaldt 1983). Furthermore, the potentially important ^{26}Mg abundance may be isotopically enhanced by yet another factor of 2 in the CRs. Past measurements suggested so (Mewaldt et al. 1980; Wiedenbeck & Greiner 1981), but more recent ones do not confirm that; however, we have no reason to expect the CRs in Orion to have the same composition as the GCRs, because the gamma-ray flux requires a more intense component of CRs in Orion.

The most important ^{26}Al -producing reactions depend on the energy available and on the composition of the accelerated particles. Below 10 MeV nucleon $^{-1}$ $^{26}\text{Mg}(p, n)^{26}\text{Al}$, $^{23}\text{Na}(\alpha, n)^{26}\text{Al}$ and $^{24}\text{Mg}(\alpha, pn)^{26}\text{Al}$ are the most important reactions with interstellar H and He. Because interstellar H exceeds He by 10-fold in abundance, and because each reaction contributes roughly equally for continuous energy spectra and

normal abundances, we will give the first reaction more attention, but only by way of example. The more difficult physical question is that of what physically occurs in star-forming regions. Our purpose is exploration of that question, rather than the presentation of a calculation of an arbitrary construction. The reaction $^{28}\text{Si}(\alpha, \alpha'pn)^{26}\text{Al}$ also comes into play near 10 MeV nucleon $^{-1}$. At higher energy nucleon $^{-1}$, $^{28}\text{Si}(p, p'pn)^{26}\text{Al}$ and other reactions come into play. The cross sections for these reactions have been studied (Skelton, Kavanagh, & Sargood 1987; Normal et al. 1981; Paul et al. 1980; Furukawa et al. 1971) and summarized (Kozlovsky, Lingenfelter, & Ramaty 1987; Clayton et al. 1977) in the literature. The above reactions are especially important if large low-energy flux exists at 5 MeV nucleon $^{-1}$, as has previously been considered in the solar disk itself (Clayton et al. 1977) rather than in the molecular cloud stage of solar formation.

The astrophysical situation envisioned by us features a large flux of low-energy ions rather than a continuum of high-energy particles. This renders the nuclear physics of the problem essentially different from the traditional cosmic-ray problem, wherein one deals with "spallation reactions." When mutual velocities exceed 100 MeV nucleon $^{-1}$, as in the measured GCRs, the breakdown of larger particles into smaller fragments is the norm. Ti in the GCRs comes primarily from the spallation of CR Fe, for example. And Li, Be, and B come primarily from the spallation of C and O. But low-energy particle fluxes near 10 MeV nucleon $^{-1}$ are the active agents in Orion. The relevant nuclear reactions are then much more target and channel specific. As a consequence the reaction $^{23}\text{Na}(\alpha, n)^{26}\text{Al}$ may be very important in Orion and in the early solar system (Ramaty et al. 1995; A. G. W. Cameron, private communication), even though it is of negligible importance for the observed GCR composition at Earth.

We illustrate typical nuclear physics of this energy range with a summary of the $^{26}\text{Mg}(p, n)^{26}\text{Al}$ cross section as a function of energy (Fig. 1). We have constructed it from data from several papers (Skelton et al. 1987; Paul et al. 1980; Norman et al. 1981; Furukawa et al. 1971). Figure 1 shows a cross section that rises rapidly above 5 MeV nucleon $^{-1}$, reaching its largest value in a 5 MeV band between 10 and 15 MeV nucleon $^{-1}$. At

FIG. 1.—Representation of the published data for the $^{26}\text{Mg}(p, n)^{26}\text{Al}$ cross section (1 mbarn = 10^{-27} cm ^{2}). Lowest energy data is by Paul et al. (1980); intermediate from Norman et al. (1981); highest from Furukawa et al. (1971). At the low energies discussed, specific reaction channels dominate the reaction mechanism. This one is fairly typical in peaking between 5 and 10 MeV nucleon $^{-1}$ and declining slowly at larger energy.

larger energies the cross section declines. This result is typical of many specific-channel reactions at these energies.

2.1. Stopping and Range of Cosmic Rays

When ^{26}Mg ions of initial energy E_0 come to rest in a thick target, the number of ^{26}Al transmutations that occur per ion is given by

$$N(^{26}\text{Al}) = \int_{E_0}^0 dE n_H \sigma(E) (dE/dx)^{-1} \text{ per } ^{26}\text{Mg stopped} . \quad (1)$$

We have calculated the stopping power dE/dx for ions moving in a molecular cloud of solar composition. Bethe's theory gives the energy loss per unit path length to be

$$-(1/\rho)dE/dx = (4\pi r_e^2 mc^2 / u\beta^2) (Z'/A) Z^2 \times \{ \ln [2mc^2\beta^2 / (1 - \beta^2)I] - \beta^2 \} , \quad (2)$$

where the quantities have conventional meanings: u is the amu, mc^2 is electron rest energy; Z is the projectile charge number; Z' and A' are the atomic numbers of the stopping element, which has mass density ρ ; and I is the mean excitation per ionizing collision. We found Bethe theory to be sufficiently accurate by simply normalizing its coefficient to measurements of the total range as found, for example, in Table of Isotopes (Lederer & Shirley 1978). For our purposes it will be most useful to show one result, the range of a ^{26}Al ion in the cloud of solar composition, which we do in Figure 2. This nuclear range will also be of significance in the subsequent two interpretations of ^{26}Al in clouds, as described below in §§ 4 and 5. The linear portions of range curves such as that in Figure 2 constitute a power-law dependence of range on energy. Figure 2, for example, is well represented by the line $y = 1.84x - 3.85$, where we use $y = \log [\text{range (g cm}^{-2}\text{)}]$ and $x = \log E (\text{MeV nucleon}^{-1})$; that is, range proportional to $E^{1.84}$. For other elements dE/dx scales in proportion to Z^2 , rendering the range inversely proportional to Z^2 , whereas the total energy is AE , where A is the atomic weight of the cosmic ray and E represents the kinetic energy per nucleon. Having found these

FIG. 2.—The range of stopping ^{26}Al ions as a function of their initial velocity (energy nucleon $^{-1}$). The stopping composition is that of the interstellar medium. Approximately, $\log [\text{range (g cm}^{-2}\text{)}] = 1.84 \log [E \text{ nucleon}^{-1}] - 3.85$ for ^{26}Al in the energy range discussed. The numerical values are comparable to the column density through molecular cloud cores (Table 2). For other ions (Z, A) of equal velocity (i.e., $E \text{ nucleon}^{-1}$) stopping in solar composition, this relation can be scaled by adding the term $\log [(A/26)(13/Z)^2]$.

simple formulae to be adequate for the astrophysical questions to be discussed, we also employ them for the question of whether CRs stop in molecular clouds (§ 3).

2.2. Yield of ^{26}Al per ^{26}Mg Cosmic Ray

Figure 3 displays the results of evaluating equation (1) as a function of initial energy E_0 for stopping ^{26}Mg . The fraction of ions transmuted in a thick target is quite small for initial energy $E_0 < 6 \text{ MeV nucleon}^{-1}$, rises sharply to near 10^{-4} per ^{26}Mg at $E_0 = 8 \text{ MeV nucleon}^{-1}$, and reaches 10^{-3} for $E_0 = 16 \text{ MeV nucleon}^{-1}$. These efficiencies for conversion are rather small, and ultimately jeopardize the proposal of Clayton (1994) suggesting them to be the source for $^{26}\text{Al}/^{27}\text{Al} = 5 \times 10^{-5}$ in molecular cloud star-forming regions. To see this, consider the star-forming matter to be a superposition of initial cloud matter plus stopped low-energy ions. To achieve the bulk ratio 5×10^{-5} with 10^{-4} ^{26}Al produced per ^{26}Mg ion for the low bombarding energy $E_0 = 8 \text{ MeV nucleon}^{-1}$, originally favored by Clayton (1994) would require half the ^{26}Mg content of that portion of the cloud to consist of stopped ions! This seems unreasonable even on the face of it; but we must seek scientific reasons to exclude it.

Take instead the efficiency 10^{-3} at $E_0 = 16 \text{ MeV nucleon}^{-1}$, which requires 5% of the ^{26}Mg to be stopped ions to achieve the desired isotopic concentration. Assume for purposes of argument that the 5% admixture fraction applies not only to $A = 26$ but to *all* atomic weights (as if the CRs also have solar composition). Each stopped ion loses $16 \text{ MeV nucleon}^{-1}$ to excitations of the gas. The energy input to the gas would then have to be $5\% \times 16 \text{ MeV nucleon}^{-1} \times 1.6 \times 10^{-12} \text{ ergs eV}^{-1} \times 6 \times 10^{23} \text{ nucleons g}^{-1} = 7.7 \times 10^{17} \text{ ergs g}^{-1}$. It is totally unreasonable for the entire $10^5 M_\odot$ of Orion clouds to radiate this energy per Myr. Therefore suppose instead that the energy loss is concentrated only in the high-density cloud cores (in which we assume that the Sun once formed), and suppose those cloud cores comprise a fraction f_{core} of the total cloud mass. The total power dissipated in that fraction by creating ^{26}Al in that same fraction (which we will argue below is where the nuclear interactions and ionization losses primarily occur) is then $7 \times 10^{17} \text{ ergs g}^{-1} \text{ Myr}^{-1} \times (f_{\text{core}} M_{\text{cloud}})$. If the Orion cloud cores total $10^2 M_\odot$, this luminosity would then be $1.5 \times 10^{53} \text{ ergs Myr}^{-1} = 4.9 \times 10^{39} \text{ ergs s}^{-1} = 1.3 \times 10^6 L_\odot$.

FIG. 3.—Yield of ^{26}Al per stopping ^{26}Mg ion as a function of its initial energy via the (p, n) reaction of Fig. 1. This yield is the integral (eq. [1]) along the path of the stopping ion. For initial energy between 15 and 20 MeV nucleon^{-1} , about 10^{-3} of stopping ^{26}Mg transmute to ^{26}Al .

Even this reduced amount is greater than the entire infrared luminosity of Orion, about $10^5 L_\odot$. It is also greater than the total power made available by all of the massive stars in Orion. Brown et al. (1994) and Blaauw (1964) have shown that only about 10 supernovae can have occurred during the past few Myr, and their total power delivered to the ISM was only 10^{52} ergs. This is at least 10 times less than the required energy on this picture. We therefore conclude that the first scenario for production of ^{26}Al is excluded on energetic grounds if the CRs have solar composition, even if only $100 M_\odot$ of cores stop the particles. For any chance of success this picture must suppress H and He acceleration, as Ramaty et al. (1995) suggested from their considerations of gamma-ray production.

The largest latitude for reduction of this power requirement is to suppose that hydrogen and perhaps helium are absent in the stopping CRs. In that case requiring 5% of ^{26}Mg and other heavy nuclei to be stopped CRs would correspond to only about 0.05% of total nucleons—reduction by a factor 100 in the mass density of stopped CRs. This could reduce the infrared power to $10^4 L_\odot$ required to make $^{26}\text{Al}/^{27}\text{Al} = 5 \times 10^{-5}$ in $100 M_\odot$ of dense cores (or $10^5 L_\odot$ if in $1000 M_\odot$ of cores, etc.). This may be reasonable if an accelerator of such CRs exists. To find such an accelerator is a physical problem required in this picture.

2.3. Anomalous Cosmic Rays

A CR composition devoid of H and He would be very unusual indeed. It would at first glance seem to require one of two things: either CRs accelerated from interior shells of supernova or presupernova (W-R) matter (which are devoid of H and He) or acceleration of the ionized atoms of low ionization potentials within the neutral-gas portion of the clouds (wherein H and He are neutral). Substantial quantities of C+, for example, occur in neutral clouds, so there may be some chance for the latter. Continuous acceleration of such ions within molecular clouds, probably by the magnetized turbulence, is a process worthy of study; but we know of no existing theoretical analysis for it and so will not address it further in this work. Ramaty et al. (1995) and others have speculated on the former approach, in their case favoring the WC ejecta; and Nath & Biermann (1994) postulated acceleration by shocks in the W-R star winds to account for the 4.43 MeV gamma rays. Bykov & Bloemen (1994) pointed to supernova-shell matter, also without convincing mechanism for selecting only those particles for acceleration. None of these authors demonstrates the preferential acceleration of atoms from supernova interiors or of Wolf-Rayet winds, in preference to the much more abundant ambient medium, which is a partner in the shocks. It is necessary to understand why supernova sources should favor acceleration of ions from within their cores when their shock waves pass so much ambient matter.

Our suggested solution for this selectivity features a known physical mechanism that also favors low energy, the likelihood of “anomalous cosmic rays,” or ACRs (Mewaldt, Spalding, & Stone 1984; Mewaldt et al. 1993). The idea of applying the ACR acceleration mechanism to Orion was first published in abbreviated form by Jin & Clayton (1995) and by Ip (1995). The known examples of ACRs in the solar system are accelerated within the solar system after neutral particles drift into the solar-wind cavity, are ionized by solar UV (or charge exchange), and are then quickly swept up by the 400 km s^{-1} solar wind (Fisk, Kozlovsky, & Ramaty 1974). This provides the first step of a two-stage accelerator. These ACRs are

observed to be sufficiently abundant to dominate the GCR at Earth below $20 \text{ MeV nucleon}^{-1}$. This is a sobering fact. They are enriched in He and O because their high ionization potentials keep them neutral until they have drifted into the heliosphere. Their enrichment at Mg and Si is not totally clear because the low flux of heavy ions makes their detection difficult; but it is not anticipated owing to their lower ionization potentials. The ACR may be H-deficient, which would help the power requirement; but the H content is also in doubt owing to the difficulty of separating the anomalous protons from those of solar particles at lower energy and GCRs at higher energy. Since H and O have equal ionization potentials it is not clear what factors enhance the O/H ratio.

For several reasons the anomalous cosmic rays in Orion may differ substantially from those in the solar system. The solar wind is a rather puny plasma flow, amounting to $n = 10 \text{ cm}^{-3}$ at 400 km s^{-1} as it passes the Earth, only about $3 \times 10^{-14} M_\odot \text{ yr}^{-1}$. By contrast a W-R star loses $10^{-5} M_\odot \text{ yr}^{-1}$ (Bieging, Abbott, & Churchwell 1989), some nine orders of magnitude greater, and at velocity near 2000 km s^{-1} . The power available for the same acceleration mechanism is clearly vastly greater. The rate of neutral drift into the wind (or associated plasma flows) may also be much greater in Orion. Very sparse neutral matter exists near the solar system (“the local fluff”), whereas an H II region is, by its very definition, a boundary between ionized and neutral hydrogen. There may well exist many local instabilities wherein neutral fingers penetrate fast-moving plasma. On very general grounds, therefore, it would be surprising to us if the ACR flux in Orion were not many orders of magnitude greater than it is observed to be in the planetary disk of the Sun.

O'Dell (1994) summarizes his work with his students delineating the complicated plasma flows in the nebula in Orion. As the photoionized matter at the molecular cloud surface accelerates almost explosively away from the cloud, it generates composition, velocity, and ionization gradients. Neutral oxygen is accelerated by 6 km s^{-1} over a mere 0.002 pc during its transition to $[\text{O II}]$, a suddenness that O'Dell sees as “a challenge for theoreticians to explain.” The $[\text{O I}]$ is churning turbulently at 10 km s^{-1} , FWHM corrected for instrumental and thermal broadening. Because O'Dell's words speak eloquently to a setting in which ACRs will certainly arise, we choose to quote his conclusion verbatim:

Nothing is static in the Orion Nebula. The ionizing star is moving rapidly into the molecular cloud, pushing the ionization front ahead of it, thus unveiling objects that had been hidden from the intense ultraviolet luminosity of $\theta^1\text{C Ori}$. Once irradiated, objects such as the Proplyds are rendered very visible through photoionization and recombination and shadowing against the primary ionization front. The interactions taking place between the jet/bullets coming from these same sources which were visible only in the infrared now become optical sources. Of course the gas in the nebula is also changing. Initially trapped in the shock compressed photodissociation region, it is then entrained in the ionization front itself. Once this happens it is rapidly accelerated away from the front, rapidly dropping to a low density and entering the general interstellar medium. The advance of the ionization front is highly irregular, depending upon the local density of molecular cloud material, so that the front becomes a luminous shroud placed over these irregularities. How fortunate that we live at a time to witness and decipher this.

It is by contrast sobering to realize that, even though we live *within* the solar wind, we cannot detect optical manifestations of its local acceleration of picked-up O^+ ions to an intensity that exceeds even that of the GCR at Earth's orbit.

Considering the prevalence of He and O in the local ACRs, even despite the Sun's poor capability for ionizing them, and considering that the neutral-ionized transition for them is much more prolific in ultraviolet-rich H II regions than at the heliosphere, we first consider that the ACRs in Orion may be He^+ and O^+ . To motivate this possibility, consider that neutrals may drift far more numerous into the H II regions and their energetic plasma flows. For that reason He and O may be much more abundantly accelerated in Orion than in the solar wind. This simple assumption therefore seems appropriate to the efforts of this work, considering that we are emphasizing widely disparate physical pictures for the Orion phenomenon. The most overabundant (relative to the GCRs) ion in the solar ACR is oxygen, with an overabundance of 39 relative to C (Mewaldt et al. 1984), whereas He is only overabundant by the factor 4. If O is also very overabundant in Orion, the excitations of $^{12}C(4.43)$ will be more readily produced by the inelastic breakoff of an alpha from ^{16}O , leaving excited $^{12}C^*$. For definiteness, we consider an ACR component in Orion to consist of He^+ and O^+ in some unknown ratio. In a preprint received just one week prior to our submission, Ip (1995) also argues for ACR mechanisms (for gamma production), although he focuses on T Tauri winds for the plasma-pickup site. This is an interesting suggestion owing to the possibility of T Tauri stars within the molecular clouds. Indeed, we go further and recognize that the Sun itself may have been the T Tauri object producing the ACR responsible for our initial ^{26}Al concentration, and that the irradiation may have been of a dust-rich disk surrounding it. This option is then very similar to the nuclear evaluations of that geometry by Clayton et al. (1977).

2.3.1. He Anomalous Cosmic Rays

Consider first the He ACR. What would be the reactions of interest for ^{26}Al production? The reaction $^{23}Na(a, n)^{26}Al$ is endothermic by 2.97 MeV, but its cross section is expected (Woosley et al. 1975) to rise very sharply above threshold and achieve its full value near 300 mbarn between $E = 1.5$ MeV nucleon $^{-1}$ and about 6 MeV nucleon $^{-1}$. This reaction can be a prolific ^{26}Al producer if large He flux is accelerated only to energies near 2–3 MeV nucleon $^{-1}$ (see Ramaty et al. 1995). At somewhat larger energy the $^{24}Mg(a, pn)^{26}Al$ reaction with a more abundant target nucleus comes into play. Its threshold is 14.58 MeV, effectively about 4 MeV nucleon $^{-1}$ for alphas, and the cross section rises to about 100 mbarn between roughly 7 and 15 MeV nucleon $^{-1}$. Because the interstellar abundance ratio is $^{24}Mg/^{23}Na = 15$ (Anders & Grevesse 1989), the latter reaction is more important if the spectrum of anomalous alphas extend upward to 10 MeV nucleon $^{-1}$, as it does in the solar system. We again adopt the picture of alphas accelerated to some specific energy, after which they enter and are stopped in the clouds. It may be noteworthy that because ^{58}Fe is five-fold more abundant than ^{64}Ni the reaction $^{58}Fe(a, pp)^{60}Fe$ will be a more efficient source of ^{60}Fe if *only anomalous alphas are accelerated*—more efficient in the sense that the ratio of ^{60}Fe to ^{53}Mn , both derived from alphas striking Fe, will be greater than it would be for proton production. The ^{53}Mn production derives from the more awkward reactions having multiple output particles, such as $^{56}Fe(a, d'pnn)^{53}Mn$, which have thresholds near 30 MeV, or from considerably less abundant

targets (e.g., ^{50}Cr). This may be significant in light of the limitations imposed by the observed ^{53}Mn abundance in solar matter (see below).

Figure 4 shows our calculation of the yield of ^{26}Al per stopped alpha particle as a function of its initial energy. At lowest energy ^{23}Na targets dominate, but ^{24}Mg targets become more important above 6 MeV nucleon $^{-1}$. The yield of 4.43 MeV gammas from $^{12}C(a, a')^{12}C^*$ is very similar but roughly a factor of 50 larger. Cross sections are shown graphically in Ramaty et al. (1979). We find that at 10 MeV nucleon $^{-1}$ initial energy, alphas are found to produce 2×10^{-6} 4.43 MeV gammas per stopped alpha from ^{12}C targets, and somewhat less from ^{16}O targets. This is a favorable production ratio $^{26}Al/4.43$ MeV. However, a severe problem again lies in the total power required. Almost 10 ergs per 4.43 MeV photon are required by alphas. To produce 2×10^{39} s $^{-1}$ of gammas requires 10^{45} s $^{-1}$ stopped alphas, each carrying 40 MeV = 6.4×10^{-5} ergs. The total dissipation 6×10^{40} ergs s $^{-1}$ will be too large. Thus accelerated alphas are no help in accounting economically for the 4.43 MeV flux from Orion. However, this does not rule out alphas as a ^{26}Al producer in smaller cloud-core mass. The most favorable speculation would be a large flux of low- E alphas striking dust-enhanced material (a disk?), where the $^{23}Na/H$ ratio is enhanced. Bombardment of the dust-rich disk (Clayton et al. 1977) by ACR He^+ rather than by solar particles may be the correct idea. The relevant energies could be too low for ^9Be production, but make abundant ^{26}Al . The production of ^9Be from C and O requires alpha energy greater than 8 MeV nucleon $^{-1}$, whereas the ^{26}Al production from ^{23}Na has just been seen to occur even at 3 MeV nucleon $^{-1}$; furthermore, in a dusty disk the Na/O ratio may be greatly enhanced over the gaseous ratio. When considering Orion today it is admittedly not encouraging to consider a bombardment that does not also account for the 4.43 MeV gammas. But that possibility underscores the problem stressed in our introduction—Orion now versus solar system then.

FIG. 4.—Yields of ^{26}Al and of ^9Be per stopped ^4He as a function of its initial energy. At lowest energy the $^{23}Na(a, n)^{26}Al$ reaction dominates production; but $^{24}Mg(a, pn)^{26}Al$ becomes stronger above 6 MeV nucleon $^{-1}$. These yields are much smaller than those of Mg cosmic rays in Fig. 3 because in this case most cosmic rays He lose energy by their collisions with light interstellar atoms, thereby bypassing the reaction channel. The production of ^9Be from C and O targets rises steeply above 10 MeV nucleon $^{-1}$, with the consequence that the production ratio $^9Be/^{26}Al$ would exceed the initial solar abundance ratio for He CRs above about 14 MeV nucleon $^{-1}$ (see also Fig. 6 in this regard).

2.3.2. Oxygen Anomalous Cosmic Rays

Another promising idea is that the ACRs in Orion are similar to those in the solar system in being more overabundant in oxygen than in other elements. We find that pure ^{16}O ACRs would indeed be economical and produce ^{26}Al abundantly as well. The cross section for production of $^{12}\text{C}^*(4.43)$ by $^{16}\text{O}(p, p'a_1)^{12}\text{C}^*$ is near 150 mbarn (Dyer et al. 1985; Lang et al. 1987) when ^{16}O interacts near 20 MeV nucleon $^{-1}$ with protons, but it fails very rapidly below 15 MeV. On the other hand, the 6.13 MeV yield from $^{16}\text{O}^*$ is near 130 mbarn between 10 and 20 MeV. Taking the attitude that the COMPTEL spectrum (Bloemen et al. 1994) is actually not very well determined with the modest number of photons they actually selected, we suppose that they measured only the sum of these two lines, with combined flux near $10^{-4} \text{ cm}^{-2} \text{ s}^{-1}$, and that the feature could even result entirely from ^{16}O ions. From the above summary of the cross sections we therefore conclude that the production of photons in the feature occurs with an average cross section near 150 mbarn throughout the range $10 < E \text{ nucleon}^{-1} < 20 \text{ MeV}$. A consequence is that ^{16}O ACRs between 10 and 20 MeV are good producers of the observed feature, but interactions with protons are inefficient below 10 MeV. However, interactions with cloud He produce the lines at lower mutual velocities owing to favorable center-of-mass effects in comparison with protons. The anomalous O^+ ions are a promising idea because they also make ^{26}Al abundantly from $^{16}\text{O}(^{12}\text{C}, pn)^{26}\text{Al}$, even to much lower energies. The reaction $^{16}\text{O}(^{16}\text{O}, apn)^{26}\text{Al}$ contributes somewhat less. Figure 5 displays our calculation of the yield of these two gamma lines as a function of initial ^{16}O energy, when stopped in solar composition.

We envision the acceleration of the O^+ ACRs as follows. Neutral O atoms drift into plasma flows and are ionized by photons from the hot stars. Charge-exchange reactions also produce the O^+ ions. They are then picked up instantaneously by the magnetic field of the moving plasma, appearing in the rest frame of the plasma as an accelerated O^+ gyroparticle with initial energy $0.5 m(\text{O})v_p^2$, where v_p is the plasma flow

FIG. 5.—Yields of 4.43 and 6.13 MeV gamma rays per stopped ^{16}O ion as a function of its initial energy. At lowest energy collisions with interstellar He are dominating the gamma production; but hydrogen becomes more important above the energy thresholds for these excitations. The 6.1 MeV gamma has slightly lower threshold a slightly higher yield. Above 16 MeV nucleon $^{-1}$ interactions with H begin producing ^9Be rather copiously, effectively limiting the applicability of the gamma-ray producing irradiation (Orion) to ^{26}Al production in solar-system matter (R. Ramaty, private communication).

speed. This results in perhaps 10–40 keV O^+ ions, which are subsequently accelerated by plasma shocks much more efficiently than the comoving thermal ions of that plasma. This sequence of events is what the solar ACRs have demonstrated. These accelerated singly ionized O^+ ACRs then penetrate the increasing field strength as they approach the clouds much more easily than do the fully ionized GCRs. In saying this we presume that their single charge explains why the ACRs can dominate the GCRs in the solar system even though both must penetrate the outward magnetized solar wind to reach the Earth. For ^{16}O range we find $\log(\text{range g cm}^{-2}) = 1.84 \log(E \text{ MeV nucleon}^{-1}) - 3.64$.

If the (4.43 MeV + 6.13 MeV) flux from Orion is $10^{-4} \text{ cm}^{-2} \text{ s}^{-1}$ as discussed above, the combined production rate of $^{12}\text{C}^*$ and $^{16}\text{O}^*$ at 500 pc must be $3.0 \times 10^{39} \text{ s}^{-1}$. If the exciting particles are taken to be 20 MeV nucleon $^{-1}$ ^{16}O nuclei, the gamma yield per stopped ^{16}O , displayed in Figure 5, is then calculated to be about 0.36%, requiring $8.4 \times 10^{41} \text{ s}^{-1}$ stopping O nuclei. The stopping power dissipated would then be $12 \times 10^{37} \text{ ergs s}^{-1}$. This is $3 \times 10^4 L_\odot$ and is not excluded by the observed infrared luminosity of Orion. If the $^{16}\text{O}^+$ initial energy $E(^{16}\text{O})$ corresponds to only 10 MeV nucleon $^{-1}$ or less, however, collisions with hydrogen are not energetic enough, so that collisions with He [center-of-mass energy $E_{\text{CM}} = 3.2E(^{16}\text{O})$] are required. These He-target reactions contribute to the 4.43 + 6.13 MeV excitation rate down to $E = 3 \text{ MeV nucleon}^{-1}$. This is a very promising approach to the severe dissipation power required by the gamma flux and must be regarded as an attractive aspect of anomalous O^+ ions. This attractiveness is not seriously compromised by a mixture of O and He in proportions found in the solar ACRs, when O/He is 10 times greater than in the GCRs (Mewaldt et al. 1984). This gives O an ACR absolute abundance about 1/5th of He, so the power in the more massive O ions is about equal to the power in He ions (since the abundance comparisons are done at the same energy per nucleon). In that case the dissipation of the He component is not great enough to materially alter the favorable conclusion. Whether anomalously accelerated H is abundant, and whether it penetrates the clouds as easily as $^{16}\text{O}^+$ if it is, is just not known, but affirmative answers would increase the power dissipated in clouds. This is a significant question, because the requirement of large resulting infrared power is a problem for the credibility of all of these CR pictures, whether their aim be production of the gamma rays from Orion or of ^{26}Al at solar-system levels in a significant fraction (about 1%) of the total cloud mass.

Oxygen ions are also good producers of ^{26}Al . At 5 MeV nucleon $^{-1}$ the center-of-mass energy (which is near 34 MeV for ^{12}C targets) is more than enough to surmount the Coulomb barrier for nuclear interactions of $^{16}\text{O} + ^{12}\text{C}$. The highly excited compound nuclear states of $^{28}\text{Si}^*$ preferentially emit a proton (leaving $^{27}\text{Al}^*$), and in most cases the residual excitation suffices for emission of a subsequent neutron. The total cross section rises with energy to 300 mbarn and still rising at $E_{\text{CM}} = 10 \text{ MeV}$, based on measurements by Kuehner & Almqvist (1964) and by Patterson et al. (1971). Those authors show that the $(^{27}\text{Al} + p)$ branch is about $\frac{2}{3}$ of the total cross section and, moreover, that excited $^{27}\text{Al}^*$ states contribute heavily to that total cross section. The reaction $^{16}\text{O} + ^{12}\text{C} = ^{27}\text{Al} + p$ is exothermic by 5.2 MeV, so all $^{27}\text{Al}^*$ excited states below $E_{\text{CM}} + 5.2 \text{ MeV}$ are reached by proton emission. This is up to about 40 MeV for $E = 5 \text{ MeV nucleon}^{-1}$, and suggests that many neutron unstable states of $^{27}\text{Al}^*$ will be populated.

Unfortunately, this is not measured, so we estimate that $\frac{1}{3}$ of the protons exit leaving $^{27}\text{Al}^*$ excitation greater than 13 MeV, the separation energy of a neutron from ^{27}Al . Putting all of these factors together suggests a cross section for ^{26}Al production equal to 70 mbarn, which we take to apply to all energies between 5 and 20 MeV nucleon $^{-1}$. This is large, almost half as large as the cross section for gamma production. Although $^{16}\text{O}(^{16}\text{O}, a)^{28}\text{Si}^*$ has comparably large cross section, the need to emit two subsequent nucleons to reach ^{26}Al renders it less productive of ^{26}Al . Since the cloud C atom abundance is about 4×10^{-4} that of the H atoms, the production of ^{26}Al at 15 MeV nucleon $^{-1}$ is about 2×10^{-4} that for the gammas, or about $6 \times 10^{35} \text{ }^{26}\text{Al s}^{-1}$. If these ions were stopped in $10^3 M_\odot$ of cloud cores, the primordial ^{26}Al concentration can almost be achieved there (compare with Table 1 below), and no doubt will be achieved in the denser cores. The reader will also note from the preceding paragraph that the production ratio $^{26}\text{Al}/\text{gamma}$ will be considerably larger for ACRs below 10 MeV nucleon $^{-1}$. That is, by placing more power in lower energy ions, the ^{26}Al production is increased relative to the known $3 \times 10^{39} \text{ s}^{-1}$ required of the excited states for gamma emission. In the absence of knowledge of the relative numbers of 5 MeV versus 15 MeV nucleon $^{-1}$ ^{16}O ions in the Orion ACRs, we conclude that adequate production of ^{26}Al in forming planetary systems by anomalous ^{16}O bombardment may be possible. This variation on picture 1 may be the most promising for nuclear transmutations by stopping heavy ions.

Anomalous acceleration of ^{12}C would achieve the same effect should it occur. In that case the known ACR mechanism would not be the relevant one, because the ACRs are deficient in carbon. Ramaty et al. (1995) proposed accelerating ^{12}C nuclei for the source of the gamma rays, invoking WC star ejecta, but they did not explain how WC star ejecta can dominate current acceleration in the absence of a WC star in Orion. A different possibility for C ions would be the sputtering of C ions from carbon dust; but that dust is likely to already be moving with the wind, in which case its ions would not benefit by the first stage of acceleration by plasma pickup. Nonetheless, if C were the active CR ion, its collisions with H and He would provide the gammas (see Ramaty et al. 1995) and those with ^{16}O would provide abundant ^{26}Al , as we described above.

The ACRs have the obvious appeal of being a known component of charged particle acceleration near ionized winds. They do not suffer from the selectivity that must be invoked for preferentially accelerating the interiors of supernovae, for

example, or for WC star winds, which are unfortunately much less massive than the prior phases of W-R star evolution which must be suppressed to avoid proton acceleration. And anomalous O ions (admixed with He) are lower producers of ^{53}Mn . Based on local observations we expect energies of 10 MeV nucleon $^{-1}$ for ACRs, which will produce gamma line widths near 10% for the 4.43 and 6.13 MeV lines. These are broad, but not nearly so broad as those from the conventional GCR. This raises the possibility that better measurements (statistics) of the observed line widths could support or rule out this possibility. The line widths were discussed by the discoverers (Bloemen et al. 1994) and by Ramaty et al. (1995), but the data do not seem to allow a firm conclusion.

The biggest nuclear obstacle to applying $^{16}\text{O}^+$ ACR to ^{26}Al production in the cloud core in the process of collapse to form the solar system appears to be the small solar abundance of ^9Be . In the early solar system the ratio appears to have been $^{26}\text{Al}/^9\text{Be} = 5.5$ (Anders & Grevesse 1989). CR interactions can easily produce a larger value, depending on the composition and energy spectrum of the CRs. Energetic ^{16}O ions produce ^9Be by nuclear collisions of sufficient energy with H and He. The relative-velocity threshold for $^{16}\text{O} + p$ is about 16 MeV nucleon $^{-1}$; and for $^{16}\text{O} + \text{He}$ it is near 7.3 MeV nucleon $^{-1}$. The cross sections are given by Read & Viola (1984). As discussed above, the production of ^{26}Al proceeds even at 1–2 MeV nucleon $^{-1}$. So the low-energy spectrum of the ACR is very important here. Figure 6 shows our calculation of the production ratio $^{26}\text{Al}/^9\text{Be}$ (solar = 5.5) as a function of initial energy E_0 when ^{16}O stops in solar gas. Overproduction of ^9Be relative to ^{26}Al occurs if $E_0 > 9 \text{ MeV nucleon}^{-1}$. Irradiation of dust-enhanced matter rather than solar gas can relax that limit substantially, because significant carbon resides in the dust, whereas H and He are almost absent. Interestingly, if the Orion gammas ($3 \times 10^{39} \text{ s}^{-1}$) result from interactions of protons above 30 MeV with O and C, the cross section ratio for production of ^9Be relative to gammas (about 0.01) will require a production of order $10^{37} \text{ }^9\text{Be s}^{-1}$. In 10^6 yr of irradiation this can produce the solar mass fraction of ^9Be in about $10^4 M_\odot$ of cloud matter. Implications of such Orion production for galactic nucleosynthesis have been remarked on by Casse et al. (1995) and by Ramaty and his coworkers (private communication). They attest to the surprising seriousness of the COMPTEL observations of Orion (Bloemen et al. 1994). Additional observations of Orion by *CGRO* are planned for summer 1995, at which time we hope for further observational guidance. For irradiation of only the solar system, on the other

TABLE 1
RADIOACTIVE BUILDUP PER MYR FROM LOW-E COSMIC-RAY COMPOSITION TRANSMUTING IN
 $10^4 M_\odot$ CLOUDS (PICTURE 1)

Excitation	CR Ion	Reaction	$\sigma(\text{mb})$	$\dot{N}(\text{s}^{-1})^a$	$A'Z/AZ^2{}^b$	Meteor
$^{12}\text{C}^*(4.43) \dots\dots\dots$	C, O	(p, p')	200	2×10^{39}	N.A.	
$^{26}\text{Al}(1.0 \text{ My}) \dots\dots\dots$	Mg	$(p, n), (a, pn)^c$	100	2×10^{37}	3×10^{-5}	5×10^{-5}
$^{41}\text{Ca}(0.14 \text{ My}) \dots\dots\dots$	^{41}K	(p, n)	100	7×10^{34}	1×10^{-8}	1×10^{-8}
$^{53}\text{Mn}(5.3 \text{ My}) \dots\dots\dots$	^{56}Fe	(p, a)	2	4×10^{36}	1×10^{-5}	8×10^{-6}
$^{60}\text{Fe}(2.2 \text{ My}) \dots\dots\dots$	^{64}Ni	$(p, p'a)$	50	6×10^{34}	2×10^{-9}	4×10^{-9}
$^{92}\text{Nb}(52 \text{ My}) \dots\dots\dots$	^{92}Zr	(p, n)	150	7×10^{32}	3×10^{-5}	2×10^{-5}
$^{107}\text{Pd}(9.4 \text{ My}) \dots\dots\dots$	^{108}Pd	$(p, p'n)$	100	1×10^{32}	1×10^{-5}	2×10^{-5}
$^{129}\text{I}(118 \text{ My}) \dots\dots\dots$	^{130}Te	$(p, p'n)$	100	4×10^{32}	2×10^{-5}	1×10^{-4}

^a $\dot{N}(\text{s}^{-1})$ is the production rate associated with $2 \times 10^{39} \text{ s}^{-1}$ excitations of $^{12}\text{C}^*(4.43 \text{ MeV})$.

^b Calculated ratios $A'Z/AZ^2$ produced per Myr in the irradiated portion of the cloud mass are respectively $^{26}\text{Al}/^{27}\text{Al}$, $^{41}\text{Ca}/^{40}\text{Ca}$, $^{53}\text{Mn}/^{55}\text{Mn}$, $^{60}\text{Fe}/^{56}\text{Fe}$, $^{92}\text{Nb}/^{93}\text{Nb}$, $^{107}\text{Pd}/^{108}\text{Pd}$, and $^{129}\text{I}/^{127}\text{I}$.

^c Revised to agree with Ramaty et al. 1995 for CRs composition [$^{26}\text{Al} = 7 \times 10^{50} \text{ Myr}^{-1}$].

FIG. 6.—Relative yields of ^{26}Al and ^9Be per ^{16}O ion as a function of initial energy. The ^9Be yield is negligible below 8 MeV nucleon $^{-1}$, but then rises to be greater than that of ^{26}Al . The production ratio for stopping O ions, Al/Be, is also shown (but multiplied by 10^{-6} to get it on the same scale). For $E_0 < 8$ MeV nucleon $^{-1}$, the production ratio is greater than the abundance ratio observed in the solar system, $^{26}\text{Al}/^9\text{Be} = 5.5$, which is shown as the cross. For this ^{26}Al -producing picture, the solar ^9Be abundance is exceeded unless the particles have energies less than 9 MeV nucleon $^{-1}$. Similar results are obtained for other compositions (see Fig. 4).

hand, it was noted long ago (Fowler et al. 1962; Clayton et al. 1977) that both abundance and isotopic anomalies of LiBeB are severe but very model dependent.

2.4. Relative Production of ^{26}Al and Other Extinct Radioactivity in Cloud Cores

Without considerations of astrophysical uncertainty, we wish to survey extinct radioactivities that should be coproduced by low-energy CRs of the known GCR composition. This is simply to understand the scope of the issues at stake. Clayton (1994) did this, but overestimated the production rate of ^{26}Al to be about $^{26}\text{Al} = 1 \times 10^{38} \text{ s}^{-1}$ for $^{12}\text{C}^*$ excitation rate at the observed value $2 \times 10^{39} \text{ s}^{-1}$. If that rate continued for 10^6 yr, as it probably has considering that the Orion complex is older than that, that production rate for ^{26}Al could be expressed as $3.2 \times 10^{51} \text{ atoms Myr}^{-1}$. Since 10^6 yr is the mean lifetime of ^{26}Al , that number of atoms would then exist in steady state there. This led Clayton to introduce the idea that ^{26}Al and other extinct radioactivities in the early solar system may have arisen in this way. His estimate should now be replaced by better calculations. Using their thorough reaction code, Ramaty et al. (1995) calculated ^{26}Al production rate for GCR composition is probably at least 15 times smaller than Clayton's estimate. That limit to the production rate of ^{26}Al does not, however, rule out the suggestion that ^{26}Al in currently forming planetary systems may be the result of an Orion-like phenomenon. The loophole is that the ^{26}Al produced in this way should not be expected to be homogeneously distributed in the molecular clouds; it need only appear in the cloud cores where stars are apparently born (e.g., Myers 1985). The molecular clouds are not of homogeneous density, but rather contain dense cores at various locations within. These dense cores will in many cases provide the lion's share of the nuclear interactions. We cannot know from the gamma-ray observations the mass of cloud to which their production is confined. If the CRs are accelerated in hot, low-density phases and bombard clouds, their relatively short range within the clouds may

restrict the ^{26}Al production to a smaller fraction of their mass, in which case the $^{26}\text{Al}/^{27}\text{Al}$ ratio would be higher in that fraction. We return to this after discussing the "raisin pudding" model in § 3. But first we wish to update Clayton's (1994) table of extinct radioactivity production.

2.4.1. Table of Extinct Radioactivity from GCR Composition

Table 1 is a revision of the table published by Clayton (1994). It surveys the consequences for other known extinct radioactivities in the solar system if the normal GCR composition were to be absorbed in 10% of the Orion cloud mass rather than uniformly by it. The calculations are normalized to yield $2 \times 10^{39} \text{ s}^{-1}$ excitations of $^{12}\text{C}(4.43)$. Therefore the isotopic ratio for extinct radioactivity depends inversely upon the mass of cloud matter that has been irradiated. Table 1 arbitrarily uses $10^4 M_\odot$, about 10% of the Orion cloud mass, for the irradiated fraction. We show in § 3 how one could understand that a modest fraction of the mass could absorb most of the irradiation for energies in the vicinity of 10 MeV nucleon $^{-1}$. We have renormalized the ^{26}Al yield to the value $7 \times 10^{50} \text{ atoms Myr}^{-1}$ based on calculations by Ramaty et al. (1995) for GCRs rather than $5 \times 10^{51} \text{ Myr}^{-1}$ as estimated by Clayton (1994). Table 1 lists the radioactive isotopic concentrations in the irradiated portion of the clouds; they are negligible in unirradiated portions. Each activation is estimated from a only single prominent reaction that is believed by us to be the primary agent for its production at low energy. Resultant isotopic ratios are compared with literature estimates of that ratio in the early solar system. We have calculated this table as a survey of the potential of these models for the extinct radioactivities as a class. Such a survey is needed to evaluate whether a new paradigm for the existence of the radioactivities in solar material may be possible. Given an understanding of what is physically occurring in Orion, it will be possible to produce more complete calculations for that picture; but at present the scientific focus must necessarily be on the attempt to formulate these physical pictures of events there. For the most part the activities expected Table 1 (based on the picture of stopping CRs within a sufficiently small mass such that ^{26}Al is adequately produced within that mass) are in the close neighborhood of the meteoritic observations. This establishes the seriousness of these issues. Clayton's (1994) thesis may be restated as follows: *if cosmic-ray production of ^{26}Al within a cloud volume reaches $5 \times 10^{-5} \text{ }^{27}\text{Al}$ per Myr, many other extinct radioactivities may also be the result of that irradiation.* Similar nuclear conclusions were reached by Clayton et al. (1977) within a different physical context, irradiation of the early solar nebula by an active early Sun. That paper and its own contexts acquire renewed meaning from the COMPTEL discovery.

We will not include in Table 1 the very ^{22}Ne -rich neon, called Ne-E(L), that is found in graphite particles within meteorites (Anders & Zinner 1993). It seems certain (Anders & Zinner 1993) that the decay of ^{22}Na within grains is required to produce the observed degree of ^{22}Ne richness ($^{20}\text{Ne}/^{22}\text{Ne} < 0.01$ and $^{21}\text{Ne}/^{22}\text{Ne} < 10^{-4}$). The best explanation (Clayton 1975) for these graphite particles is probably that they are supernova condensates that condensed graphite during the first few years of the supernovae expansions and simultaneously condensed trace amounts of $2.6 \text{ yr } ^{22}\text{Na}$, which had been freshly synthesized in those supernovae shells. If so, they are presolar particles and are therefore not relevant to general radioactivity issues in the early solar system. Nonetheless, the

early CR irradiations would make significant concentrations of ^{22}Na , so that the topic of the present paper could be relevant to them. This possibility has already been discussed at length (Clayton et al. 1977), and we have nothing to add here. In a nutshell their conclusions remain as follows. The $^{22}\text{Ne}(p, n)^{22}\text{Na}$ reaction can maintain $^{22}\text{Na}/^{22}\text{Ne} = 3 \times 10^{-10}$ in the gas phase, but it is hard to imagine graphite particles then growing sufficiently rapidly to bury the live ^{22}Na . Alternatively, if one contemplates the irradiation of solids, the $^{25}\text{Mg}(p, a)^{22}\text{Na}$ produces abundant ^{22}Na within them; but it also produces too much of the other neon isotopes for the required ^{22}Ne richness (Clayton et al. 1977) of the Ne-E(L). One would require immediate loss of the $^{20,21}\text{Ne}$ from a hot particle (retaining ^{22}Na) followed by quick cooling (within years) to retain the subsequent daughter ^{22}Ne . Any of these things may be possible, so the CR irradiations of star-forming clouds may yet prove to be relevant to these graphite particles. But these uncertainties and special considerations exceed the purposes of Table 1 and we do not include it.

2.4.2. ^{53}Mn Problem and ^9Be Problem

Both of these nuclei would be too abundant for solar data if the GCR composition is not restricted to low energy. Clayton (1994) suggested this for ^{53}Mn , and in our Table 1 we have therefore chosen to enter a favorable low-E estimate. The severity of that overproduction problem at the very high energies of the known GCRs is illustrated by very extensive transport-code calculations that have been generously provided to us by Letaw, Silberberg, & Tsao (1993), who calculate that spallation reactions in the known GCRs at Earth produce $(^{53}\text{Mn}/^{56}\text{Fe})_{\text{GCR}} = 0.76(^{26}\text{Al}/^{27}\text{Al})_{\text{GCR}}$, so that if the latter ratio were diluted to the observed value (5×10^{-5}) the corresponding ratio $(^{53}\text{Mn}/^{55}\text{Mn}) = 3 \times 10^{-3}$ would be much too high for the meteoritic observations (8×10^{-6}). But those calculations for the GCRs are dominated by the high-energy spallation reactions, for which all exit channels are energetically accessible. For $E < 10$ MeV nucleon $^{-1}$, the properties of specific nuclear channels, including their thresholds and Coulomb barriers, govern the cross section. The ^{53}Mn production is a case in point. A Hauser-Feshbach calculation at low energies (Woosley et al. 1975) where the Coulomb barrier is significant shows that the $^{56}\text{Fe}(p, a)^{53}\text{Mn}$ cross section is below 10 mbarn for $E < 10$ MeV, being only 1 mbarn at 6 MeV. It rises to about 20 mb for $E > 10$ MeV. This reaction is endothermic by only 1.06 MeV and is therefore energetically possible at even low energy. By contrast, the emission of three nucleons from $^{56}\text{Fe}^*$ following inelastic scattering has a threshold of 29.3 MeV. So either the energies must be limited to about 10 MeV nucleon $^{-1}$ or a problem over ^{53}Mn abundance (per ^{26}Al production) arises. We took the favorable (for suppression of ^{53}Mn overproduction) low-energy ($E < 8$ MeV) estimate 2 mbarn for Table 1; clearly that choice has the elements of avoiding a contradiction rather than of a conclusion. Bombardment by protons will, therefore, except at energies this small, have a problem producing ^{26}Al without overproducing ^{53}Mn . It will be another matter if the composition lacks Fe, of course. We return to this in § 5 while addressing acceleration of supernova ejecta of Type II.

The ^9Be production from C and O is too great above 20 MeV nucleon $^{-1}$ (Read & Viola 1984) for an acceptable ratio of $^9\text{Be}/^{26}\text{Al}$, although we have not listed stable ^9Be in Table 1. Ramaty and coworkers have calculated (private communication from A. G. W. Cameron during his refereeing of this

paper) that the $^9\text{Be}/^{26}\text{Al}$ production ratio is about 10 times too large for most of the compositions and energy spectra that they surveyed. The production of ^9Be has, however, a larger energy threshold than does the production of either ^{11}B (see § 1.4) or ^{26}Al , requiring careful consideration of energy spectra. We have used a very threshold-sensitive parameter E_0 by taking particles to be injected at that energy into the clouds and then stopped there. Other workers take various continuous spectra, which usually are rather insensitive to thresholds—for example, to the difference between 6 MeV nucleon $^{-1}$ and 12 MeV nucleon $^{-1}$, say. Which spectrum is more realistic depends upon the truth about low-energy acceleration. CR spectra are continuous power laws, whereas the anomalous CRs bear resemblance to a rectangular spectrum having a upper cutoff. By envisioning spectra of the latter type we intentionally improve the chances for threshold-dependent suppression of ^9Be production. Continuous spectra have severe problems with overproduction in the $^9\text{Be}/^{26}\text{Al}$ ratio. The reader is urged to be cognizant of the impact of such details. The present conclusion is that these two large overabundances (^9Be and ^{53}Mn) for bombardment above 10 MeV nucleon $^{-1}$ by the GCR composition rule out bombardment of solar material above that energy as a means of producing ^{26}Al in the solar system. This is the same conclusion demonstrated in Figure 6 for O ions. Figure 6, though calculated for ^{16}O ions, has energy dependence similar to other compositions. Table 1 is possible only below 10 MeV nucleon $^{-1}$.

2.4.3. ^{60}Fe Problem

A second problem in Table 1 is that the production of ^{60}Fe is barely adequate, and then only if the meteorites in which evidence of it has been found cooled very quickly. The observed ratio (Shokulyukov & Lugmair 1993), $^{60}\text{Fe}/^{56}\text{Fe} = 3.9 \times 10^{-9}$, may be accounted for by $^{64}\text{Ni}(p, p'a)^{60}\text{Fe}$ and by $^{58}\text{Fe}(a, pp)^{60}\text{Fe}$ —but just barely according to our cross section estimates. The second reaction might have more importance if alphas were preferentially accelerated (see ACR above). If the cooling of the eucrite meteorite body takes three Myr (Shokulyukov & Lugmair 1993), for example, the decay of the initial abundance of ^{60}Fe as $\exp(-t/2.15 \text{ Myr})$ would have required an initial solar abundance ratio greater than 1×10^{-8} . This and larger values (longer cooling times or less favorable nuclear physics) may be too great for the irradiation model. One then confronts Occam's razor: if an injection event is required for the occurrence of ^{60}Fe in the early solar system, why not attribute all extinct radioactivity to that injection, especially troublesome ^{26}Al . This would place the extinct radioactivity problem back where it has been for decades (e.g., Cameron 1993). For this very reason, extinct ^{60}Fe assumes a more important diagnostic role than it enjoyed prior to the Orion phenomenon.

2.4.4. ^{41}Ca

One success for the irradiation model is 100,000 yr ^{41}Ca , which has recently been confirmed at the level $^{41}\text{Ca}/^{40}\text{Ca} = 1.5 \times 10^{-8}$ (Srinivasan et al. 1994) in calcium-aluminum-rich inclusions within carbonaceous meteorites. Those authors realized and stated that this poses a severe threat to the paradigm for extinct radioactivity based on injection of nucleosynthesis products, requiring them to leave the star, to admix into molecular cloud material, to cool, contract and collapse and to form a solar accretion disk, to gather dust into a parent body and to form and cool the Ca-Al-rich inclusions, all in less than 0.5 Myr. In the model to be described in

the next section, the CR irradiation occurs preferentially in the high column density cloud cores where collapse may already be beginning. Decay is less a problem because the ^{41}Ca is created where the collapse is occurring. Simple inspection of ratios of abundances of target nuclei shows that if ^{26}Al is produced in this way at the correct level, so is ^{41}Ca . Table 1 uses the (p, n) reactions to show this, and the conclusion was anticipated by Clayton et al. (1977) and demonstrated explicitly by Leising & Clayton (1994) following the ^{41}Ca discovery.

2.4.5. *r*-Process Underabundances

The underproduction of ^{129}I in Table 1 is not a problem. That nucleus, along with ^{146}Sm , ^{244}Pu , and perhaps ^{107}Pd , are the residuals of continuous galactic nucleosynthesis rather than last minute production in the molecular cloud (Clayton 1983; Leising & Clayton 1994). A very interesting conclusion of those papers, though not the subject of this one, is that the *r*-process nuclei (^{107}Pd , ^{129}I , and ^{244}Pu) are deficient by a factor of roughly 10 in the early solar system in comparison with the expectations of the steady-state three-phase mixing model (Clayton 1983) for the average transport of supernova ejecta into molecular clouds. The explosive-shell activities, ^{53}Mn and ^{146}Sm , on the other hand, fit into that mixing scheme. Leising & Clayton (1994) therefore suggested that this suite of galactic nucleosynthesis products has recorded in the meteorites evidence of a historical separation of *r*-process ejecta from shell ejecta in the presolar history of the solar neighborhood. Whether that conclusion survives scrutiny or not, those nuclei are not, with the important exception of ^{53}Mn , expected to be produced primarily by the cosmic-ray irradiation of molecular cloud cores.

An alternative version of Table 1 constructed for the suggestion (§ 2.3) that anomalous He and O ions are the effective CRs in the Orion region (and other molecular clouds) has not been constructed. It may eventually be warranted, but requires much additional work on the nuclear physics questions and on the interdisciplinary uncertainties surrounding a description of the setting. Table 1 was constructed using the composition of the GCR and on assuming that their interactions occur in a mass suitable for achieving the $^{26}\text{Al}/^{27}\text{Al}$ ratio observed in the early solar system. There is a sizable power problem associated with those assumptions, as discussed above and by Ramaty et al. (1995). The discussion of § 2.3 shows that if one chooses to avoid that power problem with ACRs dominated by ^{16}O ions, the total production of ^{26}Al is $2 \times 10^{36} \text{ Myr}^{-1}$, a factor of 10 less than the entry in Table 1. That lower production rate can still achieve $^{26}\text{Al}/^{27}\text{Al} = 5 \times 10^{-5}$, but only in $10^3 M_{\odot}$ of cloud cores rather than in $10^4 M_{\odot}$ of cloud used for Table 1. A key astrophysical argument, therefore, is the expectation that smaller mass cloud cores is where the interactions occur. This comes in § 3 below.

2.5. Accelerating Ambient Hydrogen Instead of Heavy Nuclei

It may be incorrect to think that the observed gammas arise from heavy CRs striking cloud hydrogen. Both Ramaty et al. (1995) and Cowsik & Friedlander (1995) have shown in recent preprints (received during our work on this paper) that the COMPTEL measurements of the gamma lines (Bloemen et al. 1994) are consistent with having both a narrow component (caused by protons) and a broad component (caused by heavy ions). We take no stand on this because it is our judgment that the line shapes of the data do not presently warrant a conclusion on this matter. The solar system data on ACRs is also not

very helpful in clarifying acceleration of H by that mechanism. Because H and O have essentially the same ionization potentials (13.6 eV) one might expect them to be equally selected by this mechanism (Fisk et al. 1974). The data, on the other hand, have resisted clear extraction of the anomalous H from the CR H and the solar-particle H. In our evaluation of this component in Orion (see above) we have chosen to ignore this uncertainty by concentrating on the anomalous He^+ and O^+ particles, with their greater chance of penetrating the magnetic field into the clouds. For our survey of physical pictures, we feel justified in first ignoring accelerated H, whether the CR be normal galactic acceleration or anomalous acceleration. Hydrogen-dominated CRs suffer from huge power demands, as we discussed above. Ramaty et al. (1995) calculate that only about one gamma ray per erg is obtained by the GCR composition, so that $2 \times 10^{39} \text{ s}^{-1} 4.43 \text{ MeV}$ gammas requires dissipation of $2 \times 10^{39} \text{ ergs s}^{-1}$, about $5 \times 10^5 L_{\odot}$ of infrared power. That requirement is probably prohibitive.

3. MOLECULAR CLOUD CORES: A RAISIN PUDDING MODEL

Issues such as those addressed above, and also those to follow in §§ 4 and 5 presenting alternative physical mechanisms for stopping CR ^{26}Al in molecular clouds, must depend on a physical picture of the molecular clouds. There can be no assessment of CR effects in Orion without a physical framework for that assessment. Because the COMPTEL measurements have opened a new era for CR research there is no existing literature on CRs there. To facilitate this we advance a simplified picture of dense molecular cloud cores suspended within less dense molecular clouds, which are themselves imbedded either in H I cloud matter or in the hot medium. Let it be clear to the reader that in so doing it is not our presumption to be formulating a good model of this complicated situation; just as it is not our intent to model the acceleration and propagation of CRs. Rather we seek physically plausible representations of the setting in order to be able to perceive new physical possibilities for the existence of ^{26}Al in the molecular cloud cores, which is where stars appear to be forming (Myers & Benson 1983; Myers 1985; van Dishoeck et al. 1993). Those authors have shown that the larger molecular volume contains dense cores. These cores are of two classes: low mass (near $1 M_{\odot}$) and $\log n(\text{cm}^{-3}) = 4\text{--}5$ and of high mass ($10\text{--}1000 M_{\odot}$) and $\log n = 5\text{--}6$. The high-mass cores are found near OB associations and will be our primary interest in what follows. Figure 7 presents a cartoon of such a cloud-cloud core system, with magnetic field lines traced through them. The cartoon is idealized, and its scale is more like $\log R$ than R . It is offered to facilitate conception of relevant ideas. An even more detailed breakdown of cloud cores is presented by van Dishoeck et al. (1993). We reproduce some of their Table 2 in our Table 2, in which we also add the column density N through the cloud because it will be instrumental in assessing the CR interactions. Table 2 also reminds the reader that the settings are much more complex than our cartoon in Figure 7. This figure's purpose is realization of the physical ideas below.

To consider whether ^{26}Al may exist routinely in molecular clouds owing to the stopping of CRs rich in ^{26}Al , we must first evaluate the column density of clouds. This column density is for CRs analogous to the optical depth for photons, and is designated by N , the number of particles per unit area integrated through the cloud. Consider a spherical cloud having nucleon density n and total mass $M = m M_{\odot}$. Writing $n(\text{cm}^{-3}) = 10^4 n_4$ in terms of the number density $n_4 = n/(10^4$

FIG. 7.—Schematic for molecular-cloud cores within molecular clouds. For purposes of discussion, the cores are thought of as $10^{-3} M_{\odot}$ having number density $n = 10^6 \text{ cm}^{-3}$, whereas the total clouds are 10^4 – $10^6 M_{\odot}$ having $n = 10^3 \text{ cm}^{-3}$. Clearly this cartoon has nonlinear scale, more like $\log(r)$ rather than r . Magnetic field lines converge into the clouds from the surrounding ISM. Their density is still higher in the cores, which may be linked together by those fields.

cm^{-3}) we easily find for the total radius the value

$$R_{\text{cloud}} = 3.1 \times 10^{17} (m/n_4)^{1/3} \text{ cm} \quad (3)$$

and total column density $N = 2Rn$ through the cloud

$$N = 6.2 \times 10^{21} (mn_4^2)^{1/3} \text{ cm}^{-2}. \quad (4)$$

By comparison the range of ^{26}Al nuclei is (see Fig. 2 and eq. [3]) equal to $4.4 \times 10^{23} \text{ cm}^{-2}$ at $100 \text{ MeV nucleon}^{-1}$, equal to $2.3 \times 10^{22} \text{ cm}^{-2}$ at $20 \text{ MeV nucleon}^{-1}$, and is equal to $6.0 \times 10^{21} \text{ cm}^{-2}$ at $10 \text{ MeV nucleon}^{-1}$. These comparisons set the scale of the stopping CRs.

Simply for the sake of definiteness, we think of a massive molecular cloud (such as the Orion A and B complex of today or 10^6 yr ago) as a cloud of $10^5 M_{\odot}$ in which multiple cores of both classes are embedded. Imagining this as a density-contrast photo, we call it a “raisin pudding.” We take for numerical estimates the bulk density to be $n = 10^3 \text{ cm}^{-3}$ and that in the cores to be $n = 10^6 \text{ cm}^{-3}$, recognizing that this contrast is neither uniform nor abrupt. We concentrate on the massive cores having $m = 10^{-3}$. Take the mean mass to be $100 M_{\odot}$. Then the column depths of cloud and its cores are respectively, $N_{\text{cloud}} = 6.2 \times 10^{22} \text{ cm}^{-2}$ and $N_{\text{core}} = 6.2 \times 10^{23}$

cm^{-2} . The core column density is 10 times greater than the column density of the entire cloud. The physical significance lies in considering a characteristic CR energy for ^{26}Al nuclei—say, 100 MeV and lower. The range evaluations of the preceding paragraph show that these CRs penetrate the entire cloud without stopping ($100 \text{ MeV range} = 7N_{\text{cloud}}$) but are stopped with high probability in the cores ($100 \text{ MeV range} = 0.7N_{\text{core}}$). As the ^{26}Al energy drops below $100 \text{ MeV nucleon}^{-1}$, the cloud cores become thick, regardable as “cosmic-ray sponges,” whereas the clouds themselves only reduce appreciably the CR energy in preparation for stopping in the cores. Only energy less than $25 \text{ MeV nucleon}^{-1}$ will be stopped in the cloud before reaching a central core. Before considering briefly the magnetic fields we note that some of the core types in Table 2 are even thicker yet to CRs. The “hot cores” in giant molecular clouds approaching $n = 10^8 \text{ cm}^{-3}$ have column density greater than 10^{25} cm^{-2} , sufficient to stop CRs of greater than $100 \text{ MeV nucleon}^{-1}$. Because of the $E^{-2.5}$ differential CR spectrum, the most abundant CRs are those in the range of energies that will come to rest in such extreme cores. If those extreme cores represent imminent star formation, we may regard star formation sites as very good CR sponges indeed.

3.1. Magnetic Fields and Cosmic Rays

Before applying this raisin pudding model we call attention to two other effects that are expected or known to be true and that will further enhance the stopping of CR in the cores of the clouds. The first is that many cores are located near the edge of the cloud close to the OB association. This not only allows lower energy particles to reach the cores so placed, but it would on the face of things raise the probability of those cores being irradiated by particles that have been accelerated by that OB association. They are simply nearby. An even more significant enhancer of the importance of absorption by cores may be the galactic magnetic field permeating the clouds and their cores. Because of the ionization within clouds, one expects (guided by a frozen-flux contraction) that the magnetic flux (the product Br^2) will be conserved to the degree possible. Indeed, this magnetic field pressure supports the cloud cores against collapse for a lengthy period until the magnetic field can diffuse out of the cores. That ambipolar diffusion eventually allows collapse and star formation. Flux conservation would produce the expectation $B = c n^{2/3}$ for contraction of a given cloud. Even though the magnetic field actually leaks out during contraction, this tendency to conserve flux will surely produce larger magnetic fields in the denser matter. Therefore in Figure 6 the magnetic field lines are shown having higher density in the cloud than in the surrounding ISM, and, for the very same reason (prior contraction) a higher density in the cloud cores than in the cloud itself. Such general expectations seem inescapable.

Prior to its ultimate gravitational collapse the ever denser core is ripe for stopping cosmic radiation. Even more significantly, we think, the convergence of magnetic field lines into the core will guide CRs toward the cores, funneling them into the cores. This may enhance the capability of the cores to absorb most of the CR particles that enter the molecular clouds. That raises the likelihood that the ^{26}Al in cloud cores was either produced by interactions there or simply carried into the cloud cores by ^{26}Al -rich CR bombardment of the surfaces of the main cloud. The Larmor radius $r_L = mv/ZeB = 0.3 \text{ km } E_{\text{MeV}}^{1/2} B(\text{Gauss})^{-1}$ for stripped Al is no more than a relatively small $3 \times 10^4 \text{ km}$ even if B is as small as 10^{-5} gauss.

TABLE 2

PHYSICAL CHARACTERISTICS OF MOLECULAR CLOUDS^a

Type	$n(\text{cm}^{-3})$	$m(M_{\odot})$	$\langle n \rangle^b$	$R(\text{cm})^c$	$N(\text{cm}^{-2})^c$
Cold Dark Clouds					
Complex	10^2 – 10^3	10^4	10^3	1.4×10^{19}	2.8×10^{22}
Clouds	10^2 – 10^4	10^3	10^4	3.1×10^{18}	6.2×10^{22}
Cores	10^4 – 10^5	10	$10^{4.5}$	4.6×10^{17}	2.9×10^{22}
Giant Molecular Clouds					
Complex	100–300	$10^{6.5}$	200	1.7×10^{20}	6.7×10^{22}
Clouds	10^2 – 10^4	10^5	10^3	3.1×10^{19}	6.2×10^{22}
Warm clump	10^4 – 10^7	10^3	10^6	6.7×10^{17}	1.3×10^{24}
Hot cores	10^7 – 10^9	100	10^8	6.7×10^{16}	1.3×10^{25}

^a Adapted from van Dishoeck et al. 1993, Table 2.

^b Mass-weighted mean $n(\text{cm}^{-3})$.

^c From eqs. (3) and (4) using $\langle n \rangle$.

Thus the ions are closely tied to the magnetic field lines. And the field lines converge on the cores. The lines can therefore lead them into the cloud cores if the particles are not reflected (mirrored). Except for that possibility of mirroring, the B field can lead most of the low-energy CRs entering the cloud to eventually come to rest in the cloud cores. Mirroring, on the other hand, is an obstacle to the penetration of the CRs into the cloud in the first place, considering that the magnitude of B must increase as the ray enters the cloud. If the magnetic field is static the first adiabatic invariant v_{perp}^2/B is a constant, which forces the pitch angle to steepen as the ion moves into stronger magnetic field until the entire kinetic energy (constant) is transverse. The particle then mirrors. Particles having large pitch angles therefore formally mirror with only a modest (factor of 2 or 3) increase in B . Since the cloud magnetic field probably exceeds that in the surrounding low-density matter by at least the factor 3 in star-forming regions, one might question whether the low-energy CRs can even penetrate the cloud. Can they even have reached the cloud surface? Part of this answer must regard the pitch-angle scattering that accompanies an irregular magnetic field, a mechanism enabling leakage of bottled CRs into stronger fields. Skilling & Strong (1976) have advanced a more pessimistic view, arguing that the excitation of Alfvén waves by streaming CRs would prevent their entering clouds. Without faulting their argument, it seems to us that the observation by COMPTEL of inelastic gamma rays from Orion clouds speaks instead to the affirmative.

This obstacle (mirroring) can be turned into an advantage as follows. Owing to the lack of a supernova or W-R star currently in Orion, there is not a current high input of ISM energy into the surrounding low-density medium. On the face of it, the large power requirements (say $10^5 L_{\odot}$) cannot currently be provided. But the situation is very much better if the energy of past W-R stars and supernovae (perhaps 10 according to Blaauw 1994 or to Brown et al. 1994) can be saved, transformed into fast particles, and now dumped more rapidly into the Orion clouds by the opening of magnetic bottles. The mirroring of the particles may facilitate this. The mirrored particles can have their total energy within a magnetic bottle built up while the large pitch angle particles are mirrored; then pitch-angle scattering may move them to smaller pitch angles for later penetration of the clouds. These stored particles may now be entering the clouds not only because of sufficiently lowered pitch angles but also because of weakening cloud fields as a result of the ambipolar diffusion of the previously higher field from the clouds. That secular trend of weakening cloud field allows the CRs to eventually penetrate. It may even be reasonable for them to have been continuously reenergized in the surrounding low-density medium, because that medium (H II regions, essentially) is low density and ionized, so that its plasma turbulence may continuously have energized the particles. Lucy & White (1980) argued for continuous reacceleration within turbulent winds in OB cavities as a means to make good the ionization losses during acceleration there. Eichler (1979) and Ellison, Jones, & Eichler (1981) argued that a supra-thermal tail (as low as 10–100 keV nucleon⁻¹) to particle distribution functions are sufficient for much more efficient acceleration than thermal particles. Such mechanisms may enable a distribution over time of the kinetic energy of supernovae and its continuous conversion CR energy.

We acknowledge this to be a lot of conjecture about mirroring in a situation vastly different than the Earth's van Allen radiation belts, but that is exactly the point. Because of persis-

tent weaknesses in the existing paradigm for extinct radioactivity, we urge efforts to implement the CR picture until it has been shown unsustainable. Consider next the effect of turbulence within the clouds on this argument.

3.2. Infrared Power and Turbulence Power

A persistent problem in molecular clouds is the maintenance of the turbulence in their interiors. That turbulence needs a considerable source of power to maintain it. That source has been somewhat of a mystery. The turbulence is found to be strong in molecular clouds near OB associations (Zuckerman & Palmer 1974), whereas the evidence of turbulence is sometimes weak or absent in clouds more remotely located. We now propose an apparently new idea—that the power dissipated by stopping the local CRs is responsible for maintaining the turbulence. The above picture already makes it clear why in that case the turbulence would be associated with OB associations.

The CRs produce ionization at a very high rate per unit mass if they are as intense as described above. Those free electrons quickly recombine, with positive ions, or making of negative ions, or charging of dust grains. Their energy is transformed both into infrared luminosity (via grains) and into internal energy within the cold gas. Because that internal energy is raised most in the most dense parts of the cloud, it can drive a reexpansion that maintains the turbulence. Let P_{CR} be the power per gram of CR energy loss, and let ϵ_{IR} be the net emissivity per g of infrared power from the grains. Then the first law is

$$P_{\text{CR}} - \epsilon_{\text{IR}} = dU/dt + P dV/dt. \quad (5)$$

If the CR flux were uniform in space, the CR dissipation per gram P_{CR} would be independent of the density, and dense elements would gain no more power than those of less density. But this idealization applies to thin clouds only and ignores two physical effects. First, the particle ranges (Fig. 2) and cloud column densities (eq. [4]) show that the total cloud may be transparent (only a fractional energy loss) whereas the cores may be absorbing (total energy loss). CRs missing the cores may exit the cloud retaining most of their initial energy, whereas those hitting the cores may deposit their entire energy. This increases the energy input per g in dense regions. Second, the CR flux may be concentrated in proportion to the magnetic flux (as in CRs streaming along magnetic lines), thereby suggesting a nonuniform CR flux scaling as $\rho^{2/3}$. Many particles mirror near the cores, spending almost all of their time near the mirror point, concentrating their energy loss in the densest portion of their track. In a cloud of average density $\langle \rho \rangle$ having average power deposition $\langle P \rangle$, the power in cores of varying density ρ might be expressible in the form $P(\rho) = \langle P \rangle (\rho / \langle \rho \rangle)^{\Omega}$, where the exponent Ω contains the density-enhancing effects. If so, the first law would take the following suggestive form:

$$\langle P \rangle (\rho / \langle \rho \rangle)^{\Omega} - \epsilon_{\text{IR}} = dU/dt + (RT/\mu V + B^2/8\pi)dV/dt, \quad (6)$$

where $V = 1/\rho$ is the volume of a unit mass. We do not solve this equation because the assumptions leading to it are highly idealized, but the key to which we call attention is the density dependence of the first term P_{CR} . The more compressed elements absorb more power per unit mass, giving them the internal energy to fuel the reexpansion dV/dt . Thinking of the turbulence as a spectrum of alternate compressions and reexpansions owing to the high compressibility of the fluid, the CR dissipation has the property of injecting power at high com-

pression. This is the needed property for a heat engine. Power of order $10^5 L_\odot$ must be delivered to the gas by CRs to produce the 4.43 and 6.13 MeV gammas (also Ramaty et al. 1995) or to produce ^{26}Al adequately in 1% of the cloud mass (its cores). The left side of equation (6) divides that power between infrared luminosity (ϵ_{IR} losses) and mechanical power, perhaps capable of driving the kinetic energy of the turbulence. If that turbulence is itself subsequently degraded into infrared power, the P_{CR} will then have been degraded and irradiated. But the location of the IR emission may have been altered by the turbulent transport of the power. Dissipation of the turbulence may, per unit mass, be greater in the low-density portions of the cloud whereas the CR power is delivered primarily to cores. In this way the CRs may be playing a unexpected role in the maintenance of cloud turbulence.

Certainly the converse is also true. The existence of the observed turbulence has consequences for those CRs that do penetrate the molecular cloud. The magnetic field is likely to become rather tangled. The CRs attempt to follow those lines through the tangle. As they do so they will along many magnetic lines come into contact (be led into) the cloud cores of differing sizes and types (see Table 2). Most of the interactions and energy loss may occur in those cores. An extreme working hypothesis for an intercore cloud medium transparent to CRs is to assume that they will all eventually come to rest in the cores. Each low-energy CR (say, 10 MeV nucleon $^{-1}$) will require of order 100 yr to stop in mean cloud matter, which is much shorter than the time required for any structural change or for any turbulent transport. Unless the CRs are energized by turbulence within the cloud, their stopping will be within an essentially frozen cloud structure. The field lines emanating from a given core surface will trace back to a much larger area on the surface of the cloud, and that in turn to a larger Gaussian surface in the extracore medium. The tracing of these rays offers a topological, but not a dynamical, map of CR motion. These possibilities reinforce the idea of magnetic fields leading CRs toward clouds that they eventually penetrate, even if only after first being mirrored and perhaps reenergized within a turbulent low-density magnetic bottle, and within which the CRs eventually come to rest in the dense cores. Viewed this way it may not matter whether one thinks of a single $10^3 M_\odot$ core having $n = 10^5$, say, or $10^{10} M_\odot$ cores at the same density. Indeed, the 10 smaller cores at the same density have a larger summed path than the single core of their summed masses. This last realization follows simply from equation (4) and such simple comparisons as $10 m^{1/3} > (10 m)^{1/3}$. This is relevant if the guiding magnetic field lines were to pass through all the small cores, as if they are beads on a magnetic string (as in Fig. 5 of Elmegreen 1993). In such a case 10 beads, say, along a magnetic line present more opacity than one bead of 10 times larger mass. There is no such gain on a random magnetic field line of course—only on those threading the string of cores.

The reader will recognize a plethora of interesting but undeveloped physical speculation in all of this. Be reminded that we believe this speculation to be a necessary part of asking the question about the relevance of CRs to the extinct radioactivity in Orion cloud cores, and by implication in the solar system. The above speculations dress up the latter question, which has been our main motivation, with new ideas that render the whole situation more plausible. So before leaving this section we turn to one final speculation. The infrared power within Orion and other molecular clouds is concentrated in hot spots, such as BN and KL objects in Orion. The

existing paradigm for their power is gravitational energy—either from protostellar collapse or from embedded massive stars. Within the context of the present discussion we must question whether this paradigm is truly correct. The intense CR bombardment, funnelled by magnetic fields into cores capable of stopping 100 MeV nucleon $^{-1}$ ions, would also necessarily produce bright infrared regions. The angular size and intensity profile of such regions has yet to be modeled. What we call attention to is the need to establish scientific arguments both for and against the existence of infrared hotspots from CR absorption, remembering that we are speaking not of the conventional CRs but of a much more intense low-energy component that may be stopped in the cores.

This physical picture motivates the plausibility that ^{26}Al produced by CRs will be preferentially found in cloud cores. We now turn to two variations on this possibility.

4. LARGE $^{26}\text{Al}/^{27}\text{Al}$ IN GALACTIC COSMIC RAYS

Lukasiak, McDonald, & Webber (1994b) have measured $^{26}\text{Al}/^{27}\text{Al} = 0.08$ in the GCRs near 100 MeV nucleon $^{-1}$. From this they were able to conclude that the CRs near Earth are only 13.5 (+8.5, -4.5) Myr old and that they have traversed interstellar matter having an average density 0.52 (+0.26, -0.20) atoms cm $^{-3}$. Very similar results had previously been obtained from ^{10}Be in the CRs (Lukasiak et al. 1994a). The age can be calculated from nuclear models for the propagation of CRs, commonly done in a “leaky box” model with an exponential distribution of path lengths. The ^{26}Al , and indeed most of the ^{27}Al also, are produced as spallation fragments from ^{28}Si . This accounts for the surprisingly (to some) high $^{26}\text{Al}/^{27}\text{Al}$ ratio. All of the CR aluminum is young, unlike the interstellar matter in which Al up to 10 Gyr in age exist routinely. The youth of the CRs bears testimony to the need for prolific sources of acceleration capable of replenishing them every 10 ^{7} yr. The Al isotope production ratio by high-energy spallation is reasonably well known, near 0.3 depending on details. For the observed ratio to be as high as $^{26}\text{Al}/^{27}\text{Al} = 0.08$, it is necessary that the propagation time be, on average, no greater than about 10 Myr. Lukasiak et al. (1994b) calculated the “surviving fraction” of ^{26}Al to be 0.32 ± 0.09 . This is the same quantity that is called “the remainder” in the nuclear cosmochronology of radioactivity from stellar nucleosynthesis (Clayton 1985, 1988). It is the ratio of the abundance of the radioactive nucleus to the abundance it would have had were it stable. The relatively low mean interstellar density, $n = 0.5 \text{ cm}^{-3}$, is fixed by the mean time required to encounter the average 5–10 g cm $^{-2}$ of matter needed for the spallation yields required of the cosmic radiation generally. All of this makes sense and is of interest to ^{26}Al in molecular clouds, because the range calculations described above showed that the lower energy parts of the CR spectrum will indeed be stopped in the molecular clouds. Thus the picture we use here is that of the molecular clouds as “CR sponges” that slow and absorb the CRs below some energy (near 100 MeV nucleon $^{-1}$ for Al ions).

Although this high isotopic concentration of ^{26}Al may seem surprising to many, it has been expected by the community that performs the propagation calculations of CR history. For example, a standard good fit in the propagation model of Letaw et al. (1993) contains the prediction $^{26}\text{Al}/^{27}\text{Al} = 0.08$, the measured ratio. That same calculation anticipates $^{27}\text{Al}/^{28}\text{Si} = 0.2$, more than double the solar abundance ratio (Anders & Grevesse 1989) and confirming the secondary nature of even ^{27}Al in the cosmic radiation measured at Earth.

That very calculation also carries a large spallogenic abundance of ^{53}Mn , namely $^{53}\text{Mn}/^{56}\text{Fe} = 0.05$, to which we also refer owing to its importance as a constraint on these pictures of the extinct radioactivities.

From these ratios it will be evident that the ratio $^{26}\text{Al}/^{27}\text{Al} = 5 \times 10^{-5}$ may exist in a cloud core if the aluminum in that core is 0.06% stopped CRs and 99.94% cloud atoms. This is a considerably smaller injection ratio than required by picture 1 (see § 2). The question then arises of whether that admixture is physically possible. Addressing that question, we note that the same dilution would give $^{53}\text{Mn}/^{56}\text{Fe} = 3 \times 10^{-5}$, which when expressed as a Mn isotopic ratio presents the large value $^{53}\text{Mn}/^{55}\text{Mn} = 2.5 \times 10^{-3}$, at least 10^2 times greater than the value actually found in the meteorites (Lugmair, MacIsaac, & Shokolyukov 1992). This rather restrictive comparison shows immediately that the stopping CRs in cores cannot be the ordinary GCRs measured at Earth at energies exceeding $100 \text{ MeV nucleon}^{-1}$. They carry too much ^{53}Mn .

This negative conclusion might seem to banish the large CR ^{26}Al abundance to irrelevance. We think that would be premature. The large measured $^{26}\text{Al}/^{27}\text{Al}$ in the CRs reminds us that the ratio is likely to be large in any CR component if it has traversed any appreciable amount of matter. GCRs living 13 Myr on average moving (nonrelativistically, at $v = c/2$) through $n = 0.5 \text{ cm}^{-3}$ have on average traversed $N = 3.2 \times 10^{24} \text{ cm}^{-2}$. This is about 5 g cm^{-2} , more than the thickness of molecular clouds and cores (Table 2). It is this long path length that has built up ^{26}Al and ^{53}Mn from ^{28}Si and ^{56}Fe , respectively. The ratio $^{28}\text{Si}/^{56}\text{Fe}$ is solar in the CRs (Mewaldt 1983). We must, however, consider that the CRs in Orion may differ significantly from the mean galactic at Earth. If they are “younger,” they have been through smaller column density than the measured GCRs. They can still have built up ^{26}Al with a smaller path and their surviving ^{26}Al fraction might be unity, whereas the ^{53}Mn might not have had enough time ($t_{\text{mean}} = 5.3 \text{ Myr}$) to have been built up to its full abundance. These differences could enhance $^{26}\text{Al}/^{53}\text{Mn}$ by about one order of magnitude. That enhancement can be much larger if the Orion CRs have a depleted Fe/Si abundance ratio (see below).

The mean GCRs are not of sufficiently large flux to produce either the 4.43 MeV gamma rays or to produce enough ^{26}Al by stopping. But the numbers for the latter can be sufficiently encouraging with favorable assumptions to warrant further evaluations. For example, suppose that all of the CR flux that strikes the surface of a molecular cloud enters it, and suppose further that it all comes to rest in dense cloud cores. Taking the host cloud to have radius $R = 20 \text{ pc}$, which gives it surface area $A = 4\pi R^2 = 4 \times 10^{40} \text{ cm}^2$, the observed ^{27}Al differential flux at Earth (Lukasiak et al. 1994b) $d^2F/dE d\Omega = 82 \times 10^{-6} (\text{m}^2 \text{ MeV s ster})^{-1}$ allows an estimate of the number of ^{26}Al entering the cloud in a million years. The measurement covers the energy range 77–206 MeV nucleon $^{-1}$, an energy region in which the flux is flat owing to the solar modulation. Indeed, the observed CR flux for all elements is roughly flat between 100 and 1000 MeV (Garcia-Munoz, Mason, & Simpson 1973). Taking the CR spectrum in Orion to also be flat between 100 MeV and 1000 MeV, which is very conservative because were it not for solar modulation the flux at Earth would probably increase as E declines below 1000 MeV nucleon $^{-1}$, one calculates a ^{27}Al CR current through the cloud surface to be $4\pi R^2 (4\pi d^2F/dE d\Omega) (900 \text{ MeV}) = 1.2 \times 10^{50} \text{ Myr}^{-1}$. The ^{26}Al is 12

times less. The resultant ^{26}Al injection rate, $1.0 \times 10^{49} \text{ Myr}^{-1}$, is enough to create the ratio $^{26}\text{Al}/^{27}\text{Al} = 5 \times 10^{-5}$ in $100 M_{\odot}$ of stopping matter (e.g., 10 dense cores of $10 M_{\odot}$ each). It clearly fails by 10^3 to create the same ratio over the entire $10^5 M_{\odot}$ of a molecular cloud complex, but that larger mass at lower density may be transparent to the ions and therefore not be ^{26}Al -rich. These numbers may even be conservative. The actual CR flux in Orion may be larger than at Earth owing to the reacceleration of low-energy CRs there. And the flux at Earth should perhaps be increased by at least a factor of 10 owing to the solar magnetic-field modulation between 100 and 1000 MeV. If the spectrum actually continued its observed high-energy $E^{-2.5}$ slope down to 100 MeV, the integral flux would be greater by the factor $(1000/100)^{1.5} = 30$. In short, the ^{26}Al current into the cloud may be a factor 10^2 greater than the conservative estimate above based on terrestrial observations. So injection in this manner, by fast particles as opposed to injected ^{26}Al -rich plasmas ejected by conveniently located stars, may easily account for the ^{26}Al in forming stars if they can be preferentially stopped in the cores.

The constraint is the high GCR abundance of ^{53}Mn . It sets the limit to the possible admixture of normal CRs into molecular cloud cores. To avoid this limit we might not only have to appeal to the youth of the CRs, as described just above, but also find reason for the CRs in Orion to have a larger ratio Si/Fe than the terrestrial GCRs (which are equal to solar abundances in that ratio). The best hope for that will be a local acceleration that is deficient in Fe. The 5–10 core collapse supernovae over the past few Myr (Brown et al. 1994) have ejected a Si/Fe ratio that is about 10-fold solar (Weaver & Woosley 1993; Table 12), so use of that material for the locally accelerated CRs could provide the remainder of the needed enhancement. Still more might be found in the ratios of gaseous Si and Fe atoms expelled from supernovae. If the metals at the slow-moving cores of supernovae preferentially condense into metal droplets, as Clayton's (1981) chemical memory theory of the ^{48}Ca – ^{50}Ti – ^{54}Cr – ^{62}Ni correlation of endemic isotopic anomalies suggested, the locally accelerated CRs might be sampling a much enhanced Si/Fe gas-atom ratio owing to that chemical fractionation. Any good scientific reason to motivate an enhanced Si/Fe ratio in young CRs accelerated in Orion should be discovered and elucidated before concluding from the ^{53}Mn limitation that implantation of CRs cannot explain the high ^{26}Al content of the early solar system.

5. SPECIAL COSMIC RAYS FROM W-R AND SUPERNOVA EJECTA

It makes good sense to take the Orion cloud complex as typical of star-forming regions. Indeed that supposition underlies the entire implication of cosmic irradiation of star-forming regions, because Orion was so surprisingly visible to COMPTEL (Bloemen et al. 1994). In a very thorough and fascinating study, Brown et al. (1995) have shown that the Orion region has probably experienced five to 10 Wolf-Rayet stars and/or Type II core-collapse supernovae. These recent events (past 10 Myr) have ejected a lot of ^{26}Al into the hot gases between the broken cloud fragments. It must be considered that that matter may have been preferentially accelerated to about 10 MeV nucleon $^{-1}$ and stopped in the clouds after entering them. This is our third picture of CR responsibility for ^{26}Al in the clouds, but only in the star-forming clouds adjacent to previous O association formation.

The mass of ^{26}Al ejected by massive stars is substantial. The question is, has always been, can it enter molecular cloud cores within 10^7 yr. The O stars, H II regions, stellar winds, and supernova shock have prepared such a hot and almost explosively expanding compact bubble, pushing cloud material apart, that the slower moving supernova core material, which moves out into that prepared bubble, has numerous obstacles to being admixed as a plasma into surrounding molecular cloud material. If it were able to cool and join the cloud mass rather than flow away in hot wind, it would be attractive to regard this form of self-enrichment of a molecular cloud as the origin of ^{26}Al within. But it has not been successfully demonstrated that this outcome is plausible. This difficulty reaffirms the importance of the discovery of extinct ^{26}Al in meteorites.

What has not been considered previously, however, that the ^{26}Al might enter the cloud as individual low-energy CRs and simply stop. Each W-R star may eject several $10^{-5} M_{\odot}$ of ^{26}Al from its original H-burning core (e.g., Prantzos 1991); and the core-collapse Type II supernova (SNII) may eject near $10^{-4} M_{\odot}$ of ^{26}Al (Weaver & Woosley 1993). In an OB association one of these events may be occurring every Myr for a duration of several Myr, as in Orion (e.g., Brown et al. 1995). Consider only the $10^{-4} M_{\odot}$ from a single SNII core in what follows. That is a sufficient mass of ^{26}Al to produce the solar ratio $^{26}\text{Al}/^{27}\text{Al} = 5 \times 10^{-5}$, which corresponds to only $3 \times 10^{-9} M_{\odot}$ of ^{26}Al per solar mass of cloud core, through $3 \times 10^4 M_{\odot}$ of cloud—if it could quickly get in. If only 1% of that Al is accelerated and funneled by magnetic tubes into the cloud cores, it can contaminate $300 M_{\odot}$ of such cores at the indicated level. The contamination ratios also seem feasible, even if they had seemed implausibly large prior to the COMPTEL observations. The ratio $^{26}\text{Al}/^{27}\text{Al} = 0.006$ characterizes the oxygen cores of SNII, from which most aluminum arises (Weaver & Woosley 1993). To reach the observed solar ratio, therefore, the cloud-core Al must contain about 1% stopped CRs from the SNII core. But because elemental Al is overabundant by a factor 10 in those SNII, the cloud core need only be 0.1% stopped CRs by mass if those CRs were to consist only of heavy ions. The energetics of this are not out of reach either, being similar to the stopping of CR Al in the previous § 4. We will not go through them again. Our point is instead the physical difference of this CR mechanism from the ones of the previous sections.

The astrophysical question would be the physical grounds for the supernova shocks to accelerate preferentially the matter from the He cores of SNII. Why should acceleration select such matter? These cores are overwhelmingly ^{16}O , containing the ^{26}Al and ^{27}Al . Once the SN ejecta has been mixed into surrounding matter, the ^{26}Al is hopelessly diluted; so late acceleration, acceleration long after ejection, would not work. The mechanism will have to focus on the distinguishing feature of this ejecta—namely, that it is initially moving very rapidly. The ^{16}O and Al is initially moving outward at $100 \text{ keV nucleon}^{-1}$. Plasma shocks have to seize on that head start (in comparison with ambient Al) and accelerate those particles specifically upward to $10 \text{ MeV nucleon}^{-1}$. A lengthy literature argues that this might indeed be the case (e.g., Eichler 1979; Ellison et al. 1981). The kinetic energy of the SN core (10^{51} ergs) is enough to accelerate 10^{32} g of matter to $10 \text{ MeV nucleon}^{-1}$, about 1% of that SN core mass. And, as stated above, that 1% so accelerated would be enough to seed $300 M_{\odot}$ of cloud cores with the observed initial solar concentration of ^{26}Al . Eichler (1979) concluded from this theory that half the postshock pressure will be

from CRs, in which case having 1% of the particles have energy (10 MeV), 100 times the postshock kT (100 keV), is in the right range for this admixture.

6. CONCLUSION

These formulations of competing physical pictures suffice for our present purpose. Long-term critical assessment is now needed to ascertain whether a new paradigm for the existence of ^{26}Al and other short-lived extinct radioactivities in molecular cloud cores may be warranted. We are content to have created a physical assessment of several new possibilities for CR production of those special nuclei in the early solar matter. We have shown that if the COMPTEL data holds firm, it will be hard to avoid extinct radioactivity in the cloud cores. The COMPTEL data forces surprising boldness in search of explanation of the gamma rays. The extinct radionuclei have always posed challenges.

It now appears that a CR produced ratio near 10^{-5} for $^{26}\text{Al}/^{27}\text{Al}$ may exist routinely in those molecular cloud cores near OB associations. If the solar system formed in a molecular cloud on the edge of a CR accelerating region somewhat like Orion, the value $^{26}\text{Al}/^{27}\text{Al} = 5 \times 10^{-5}$ found in meteorites of the solar system may reflect just such CR production. This would alleviate a very old puzzle: namely, why was the early solar system 10-fold richer in ^{26}Al than the bulk ISM is today? Attempts to answer this question in other ways have centered on requiring a neighboring supernova or asymptotic giant branch (AGB) star to have ejected a ^{26}Al -rich fluid into the presolar cloud (Cameron 1993; Wasserburg et al. 1994) while that AGB star was fortuitously passing the solar cloud core, itself hovering on the brink of collapse. A convincing likelihood for such a scenario has not been established; but it is predicated primarily on the belief that some nearby object to the collapsing Sun must necessarily have synthesized ^{26}Al -bearing ejecta and quickly admixed the enriched gas into the solar cloud. Kastner & Myers (1994) find the AGB scenario to have low a priori probability. One can adhere to it only by regarding the solar system as rare and atypical (e.g., most stellar disks do not contain ^{26}Al), and even then by supposing that the AGB star must have caused the solar collapse in order to synchronize the two events (Cameron 1993). Though possible, many find discomfort with these somewhat anti-Copernican requirements. Was the solar birth really one of a kind, unique in its ample ^{26}Al activity, or was it typical for low-mass planetary systems? Philosophy cannot determine this.

Irradiation of the early solar system by fast particles is not in itself a new idea. It has had several reincarnations (e.g., Fowler et al. 1962; Clayton et al. 1977; Caffee et al. 1988), depending in form not only upon the imagined state of the nebula and the source of the fast particles, but also on the scientific motivations of the authors. Our treatment has introduced irradiation of dense cores within clouds by particles accelerated in nearby OB associations. We also introduced the relationship between the nuclear gamma rays detected by COMPTEL and the accompanying nuclear transmutations in those cores. We introduced a natural reason for short-lived radioactivity to have its greatest concentration in the cores that are most dense and therefore closest to collapse. We have described three distinct physical pictures for this.

Six physical obstacles to these pictures have been identified and partly circumvented: (a) the large ionizing power that must be dissipated by the stopping CRs; (b) the large power required to accelerate those CRs; (c) the mechanism of accel-

ation capable of selecting an acceptable composition; (d) penetration of CRs into stronger magnetic fields of clouds; (e) in the case of the solar system, the ^9Be and ^{53}Mn overabundances unless the particles have energy less than 10 MeV nucleon $^{-1}$. For irradiations more energetic than 10 MeV nucleon $^{-1}$, the extinct radioactivity ^{53}Mn in meteorites is more easily interpreted as an irradiation product than is ^{26}Al ; (f) difficulty in producing enough ^{60}Fe (dependent on unknown cooling time of meteorite).

So severe are those combined constraints that the attempt would be given up were it not for the surprisingly large numbers of gamma rays from Orion and of ^{26}Al nuclei in the early solar system. Both remain major puzzles. If acceptable irradiation model can be found, we suggested that its ionizing power, not gravitational contraction, is the power source for infrared cloud hotspots, and we also suggested that it drives the ubiquitous turbulence found in clouds near OB associations.

As a final point we observe that it is not strictly necessary in these pictures to require the Sun and planets to also have contained ^{26}Al . The intense irradiation could have occurred following the initial collapse of the Sun but while infall continues (probably within 10^5 yr). The Jovian planets may also have accumulated prior to the meteorite parent bodies. In that case most of the massive objects could have been free of ^{26}Al . The continuing infall onto the solar accretion disk could have been the only infall to have achieved the ratio $^{26}\text{Al}/^{27}\text{Al} = 5 \times 10^{-5}$ by virtue of the (in this case *sudden* CR irradiation). We take no position on this because the relative temporal sequence for the formation of Sun, planets, and meteorite parent bodies is not well understood. One advantage, however, of having ^{26}Al only in the late infall would be a temporarily changing ratio of $^{26}\text{Al}/^{27}\text{Al}$ in the matter falling onto the disk. This might allow Al-rich objects containing vastly different concentrations of ^{26}Al to coexist side by side in the regolith of the meteorite parent bodies; for that puzzling occurrence is exactly what is observed, and is otherwise attributed to very large time differences (7 Myr) between formation

times of similar adjacent Al-rich objects or to fossil objects. Calls for ^{26}Al heterogeneity (e.g., MacPherson, Wark & Armstrong 1988; Virag et al. 1991) might instead be interpreted as a temporal change in the concentration of ^{26}Al in the infalling matter. Any observed tendency for ^{26}Al -bearing CaAl-rich inclusions to differ isotopically in stable heavy elements from those CAIs (FUN inclusions) that may not bear ^{26}Al could reflect such temporal change during accretion onto the solar disk. *Compton Observatory* measurements of gamma rays from the Orion clouds may have put new spin onto the conundrums surrounding solar ^{26}Al .

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