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Cosmic-Ray Extinct Radioactivity in Molecular Clouds

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COSMIC-RAY EXTINCT RADIOACTIVITY IN MOLECULAR CLOUDS:

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We propose that live ^{26}Al in the early solar system and the large mass of ^{26}Al (1.5 $M_\odot$) in the galaxy today have different sources. By making ^{26}Al in cores where stars form, awkward "mixing in" is avoided.We present three distinct pictures attributing ^{26}Al and other extinct radioactivity within molecular-cloud dense cores to cosmic-ray irradiation of those cloud cores:

(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 [1];

(2) stopping of low-energy galactic cosmic rays, which carry the very large radioactivity $^{26}Al/^{27}Al = 0.1$ and which we argue to be stopped in the cloud cores;

(3) stopping of particles preferentially accelerated from local ejecta of supernovae and WR star winds, which carry activities as great as $^{26}Al/^{27}Al = 0.01$ from those events

For discussion of these pictures we introduce a magnetized raisin-pudding model of molecular clouds and their imbedded 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 $^{26}Al/^{27}Al$ ratios than does the bulk of the molecular clouds. We envision a simplified picture of dense molecular-cloud cores suspended within less dense molecular clouds, which are themselves imbedded either in HI cloud matter or in the hot medium. The larger molecular volume contains dense cores of two classes: low mass (near $1M_\odot$) and log $n(cm^{-3})$ = 4-5 and of high mass ($10\text{-}1000M_\odot$) and log n= 5-6 [2]. The high-mass cores are found near OB associations and will be our primary interest in what follows. Figure 1 presents a cartoon of such a cloud-cloud core system, with magnetic filed lines traced through them.

The column density N through the cloud determines cosmic-ray stopping interactions. With density $n=(10^4 cm^{-3})n_4$, total mass $M= mM_\odot$ and R the cloud (or core) radius

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

and total column density N = 2Rn is

$$N = 6.2 \times 10^{21} (m\, n_4^2)^{1/3} \quad cm^{-2}$$

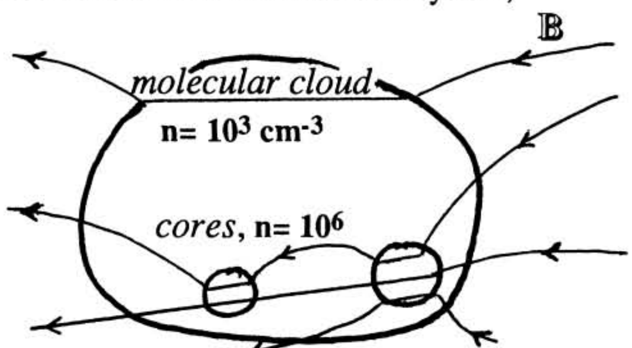

Fig. 1. Cores, clouds and external magnetic field

The range of ^{26}Al nuclei is 4.4×10^{23} cm^{-2} at 100MeV/nucleon, 2.3×10^{22} cm^{-2} at 20 MeV/nucleon, and 6.0×10^{21} cm^{-2} at 10 MeV/nucleon. These comparisons set the scale of the stopping cosmic rays. We envision a massive molecular cloud (such as the Orion A and B complex) as a cloud of 10^5 $M_\odot$ in which multiple cores of both classes are imbedded. We call it a magnetized "raisin pudding". Magnetic field lines, which the CR follow, focus on the cores.

For numerical estimates take bulk density to be $n = 10^3$ cm^{-3} and in cores $n = 10^6$ cm^{-3}, although this contrast is neither uniform nor abrupt. We concentrate on the massive cores having m = 10-10^3. Take the mean mass to be 100$M_\odot$. Then the column depths of cloud and its cores are respectively: $N_{cloud} = 6.2 \times 10^{22}$ cm^{-2} and $N_{core} = 6.2 \times 10^{23}$ cm^{-2}. The core column density is ten times greater than the column density of the entire cloud. The range evaluations for ^{26}Al show that these cosmic rays penetrate the entire cloud without stopping (100 MeV Range = 7 N_{cloud}) but are stopped with high probability in the cores (100 MeV Range = 0.7 N_{core}). As the ^{26}Al energy drops below 100 MeV/nucleon, the cloud cores become thick, regardable as "cosmic-ray sponges". We normalize to rates of $^{12}C^*$(4.43 MeV) and $^{16}O^*$(6.13 MeV) gamma rays (3×10^{39} s^{-1}) emerging from the clouds in Orion [3].

Picture 1 is plagued by very large power requirements if accelerated protons are required for the gammas, and by ^7Li and ^{53}Mn overproduction. Nonetheless, we identify promising extinct radioactivity that accompanies $^{26}Al = 5 \times 10^{-5}$ Al if produced by low-energy cosmic rays of standard composition. More promising versions of picture 1: (a) anomalous acceleration [4] of ^{16}O ions to several MeV/nucleon, which stop in $10^3 M_\odot$ of cores making the gamma lines and $^{26}Al = 5 \times 10^{-5}$ Al there with acceptable 3×10^4 $L_\odot$ power; or (b) H-and-He-free CR making ^{26}Al from stopping Mg and Si [4] in a comparable core mass. It is the stopping power of cores that allows ^{26}Al production to be ample precisely where the solar systems are actually forming.

Picture 2: Measured $^{26}Al/^{27}Al = 0.08$ in the galactic CR [5] near 100MeV/nucleon shows that cosmic rays near Earth are only 13.5 (+8.5,-4.5) Myr old and have traversed average density 0.52 (+0.26,-0.20) atoms cm^{-3}. Our range calculations show ^{26}Al CR below 100MeV/nucleon will stop in molecular-cloud cores. $^{26}Al/^{27}Al = 5 \times 10^{-5}$ may exist if heavy elements in that core are 0.06% stopped cosmic rays and 99.94% cloud atoms. This is a considerably smaller ratio than required by picture 1. CR ^{53}Mn is x100 too large, however, so a special Fe-poor source is required. But Si/Fe is tenfold enhanced in supernova ejecta, and reacceleration for only 0.5 Myr by nebular turbulence enhances $^{26}Al/^{53}Mn$ by another tenfold.

Picture 3 yields similar results if supernova or WR particles are preferentially accelerated and stop in cores. 10^{-4} $M_\odot$ ^{26}Al from a single SNII is a sufficient mass to provide $^{26}Al/^{27}Al = 5 \times 10^{-5}$ through 3×10^4 $M_\odot$ of cloud--*if it could quickly get in.* Although SN plasma itself can not admix into clouds, about 1% of its Al is accelerated before mixing and funneled by magnetic tubes into the cloud cores, contaminating 300 $M_\odot$ of such cores at the indicated level.

Compton GRO has opened a new era coupling cosmic ray research and extinct radioactivity. Each picture affords a new approach to ^{26}Al, ^{41}Ca and ^{53}Mn in the early solar system.

REFERENCES: [1] Clayton, D. 1994, *Nature*, **368**, 222; [2] van Dishoeck *et al.* 1993, in *Protostars and Planets III* ; [3] Bloemen *et al.* 1994, *A & A*, **281**, L5; [4] L. Jin and D.Clayton 1995, *Lunar Planet Sci.* **26**; [5] Lukasiac, A. *et al.* 1995, *Ap. J.*, in press.