1995

Anomalous-Cosmic-Ray Origin of 26Al in Molecular Clouds

Liping Jin
Clemson University

Donald D. Clayton
Clemson University, claydonald@gmail.com

ANOMALOUS-COSMIC-RAY ORIGIN OF ^{26}Al IN MOLECULAR CLOUDS;

Liping Jin and Donald D. Clayton, Clemson University, Clemson SC 29634-1911

Measured 4.43 and 6.13 MeV gamma rays from the Orion molecular clouds [1] revolutionize cosmic-ray physics by providing a new laboratory, bombarded by cosmic rays more intense and of different composition than measured at Earth. This CGRO discovery leads to new pictures [2,3] of the origin of extinct radioactivity in molecular cloud dense cores, where solar systems form. We introduce a known local mechanism for low-energy cosmic rays, "anomalous He^+ and O^+ cosmic rays", or ACR [4]. Solar ACR are accelerated after neutral particles drift into the solar-wind, are ionized by solar UV (or charge exchange) and then spiral at 400km/s in solar wind. Second stage acceleration occurs at the heliosphere. Returning ACR dominate the galactic CR below 20MeV/ nucleon. They are He^+ and O^+ because high ionization potentials keep He and O neutral until within the heliosphere. Single charge after acceleration facilitates penetration through magnetic fields. Solar wind is a puny plasma flow, only n=10 cm^{-3} at 400 km s^{-1} (3 x 10^{-14} $M_\odot$ yr^{-1}). By contrast a Wolf Rayet star loses 10^{-5} $M_\odot$ yr^{-1} , nine orders of magnitude greater, at velocity near 2000 km s^{-1}. Power available for ACR is clearly vastly greater. Neutral drift into winds (or other plasma flows) is much greater in Orion. Neutral matter is rare locally ("the local fluff"), whereas an HII region (Orion) is a boundary between plasma and neutrals. ACR flux in Orion will greatly exceed that in the heliosphere, as needed. They enter the clouds, making gammas and ^{26}Al.

Most overabundant (relative to the galactic CR) ion in the solar ACR is oxygen, overabundant by 39 relative to C [4], and He is overabundant by 4. O^+ ACR excite 4.43 by $^{16}O(p,p'a_1)^{12}C^*$ and 6.13 by $^{16}O(p,p')$. ^{26}Al results from $He(^{23}Na,n)$ and $He(^{24}Mg,pn)$ and from $^{16}O(^{12}C,pn)$. The cross section for production of $^{12}C^*$ by $^{16}O(p,p'a_1)^{12}C^*$ is near 150 mb when ^{16}O interacts near 20 MeV/nucleon with protons; but it falls very rapidly below 15MeV. On the other hand, the 6.13 MeV cross section from $^{16}O^*$ is 130 mb between 10 and 20 MeV. Figure 1 displays the yield of ^{26}Al from stopping He CR as a function

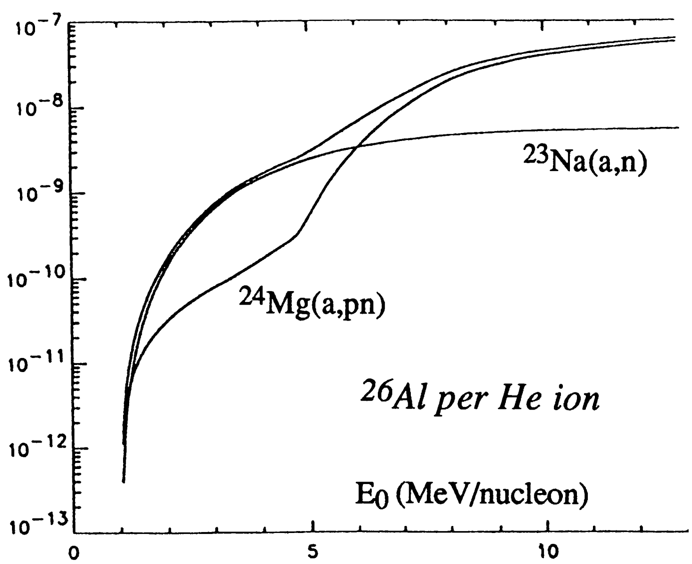

Fig. 1. Calculated ^{26}Al yield (per stopped He) using cross section summaries by Reuven Ramaty

of their initial energy. Figure 2 displays the yield from stopping ^{16}O (in solar composition) of these two gamma lines as a function of initial ^{16}O energy. The (4.43 MeV + 6.13 MeV) measured Orion flux [1] is 10^{-4} cm^{-2} s^{-1} ; so, gamma production at 500pc is 3.0×10^{39} s^{-1}. ACR are [4] 20MeV/nucleon ^{16}O nuclei, so gamma yield is 0.36%, requiring 8.4×10^{41} s^{-1} stopping ^{16}O nuclei. Stopping power is 12×10^{37} erg s^{-1} $=3 \times 10^4$ $L_\odot$ and is not excluded by the observed infrared luminosity of Orion. This makes ^{16}O ACR preferable to alphas, because 10^7 $L_\odot$ is dissipated making the gammas from alphas. So He ACR are not economical for the gammas, although Fig. 1 shows they are useful low-energy producers of ^{26}Al, especially if the He irradiation of dust enhanced regions applies.

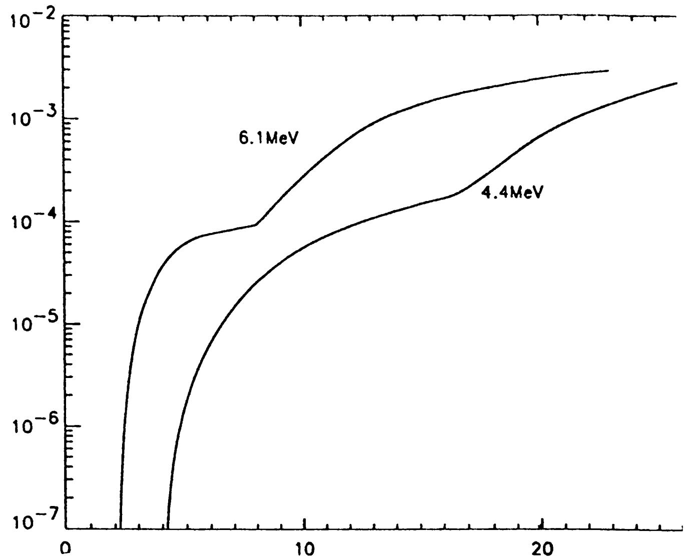

Fig. 2. Calculated gamma yield (per stopped ^{16}O)

Oxygen ions produce ^{26}Al by fusion with ^{12}C to excited states of $^{28}Si^*$, emission of a proton (to $^{27}Al^*$), and in most cases excitation suffices for emission of a subsequent neutron. The total cross section rises with energy to 300 mb (still rising) at E_{CM}=10 MeV [5]. Putting all factors together suggests a cross section for ^{26}Al production equal to 70 mb between 5 and 20 MeV/nucleon. Since the cloud C atom abundance is 4×10^{-4} that of the H atoms, the production of ^{26}Al at 15 MeV/nucleon is 2×10^{-4} that for the gammas, or 6×10^{35} ^{26}Al s^{-1}. If these ions are stopped preferentially in 10^3 $M_\odot$ of cloud cores [3], the primordial ^{26}Al concentration 5×10^{-5} can be achieved there, even though not uniformly in the clouds, which are too transparent. Our summary picture is this: acceleration of anomalous $^{16}O^+$ ACR, which penetrate the clouds and follow magnetic lines into the star-forming cloud cores, where they stop owing their to increasing density, making ^{26}Al preferentially in those cores.

Supported by The W. M. Keck Foundation grant for study of the origin of natural radioactivity and by NASA.

REFERENCES: [1] Bloemen, H. *et al.* 1994, *A & A* **281**, L5; [2] Clayton, D. 1994, *Nature* **368**, 222; [3] Clayton, D.D. & Jin, L. 1995, *Lunar Planet. Sci* **26**; [4] Mewaldt, R. et al. 1980, *Ap.J.* **225**, L95; [5] Kuehner, J.A. & Almqvist, E. 1964, *Phys. Rev.* **134**, B1229