pointed out (*2*), this might be crucial for the energy transfer from LH1 to the reaction center. A more efficient energy transfer allows a larger distance between the LH1 ring and the two strongly interacting chlorophyll-like molecules in the reaction center that trap the excitation; the separation serves to prevent charge transfer back to LH1 after ionization.

Finally, the characterization of an individual LH2 complex is a theorist's dream come true in molecular spectroscopy. With the structure known, detailed comparisons between theory (*10*) and experiment become possible. As one of the first examples of single-molecule spectroscopy in strongly interacting systems, van Oijen *et al.*'s study bridges the gap between studies of narrow zero-phonon lines ($10^{-3}$ $cm^{-1}$) at low temperatures and those of broad bands (100 $cm^{-1}$) of dye molecules at room temperature (*11*). The spectral resolution of 1 $cm^{-1}$ in (*1*) is compatible with the use of short (picosecond) laser pulses and could lead to the fascinating prospect of time-resolved investigations of single molecules.

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PERSPECTIVES: COSMOCHEMISTRY

# Through an Hourglass Darkly

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How can we learn about about the early history of our solar system and the recent history of our galaxy? Astronomers and cosmochemists use a suite of radioactive isotopes as chronometers to study these important scientific questions. By comparing the measured abundance of an accumulated daughter nuclide and the inferred initial abundance of the parent radioactive species, these isotopes can serve as hourglasses that determine the time since the initial radioactive abundance was set. Among the hourglasses used, $^{26}Al$ [with a half-life ($\tau_{1/2}$) of $7.15 \times 10^5$ years] has proven to be one of the most valuable but also one of the most puzzling. Astronomers have used this isotope to great advantage in recent years to understand star formation in our galaxy. But cosmochemists are still struggling to determine how $^{26}Al$ can help them understand the conditions under which the solar system formed.

Aluminum-26 was the first radioactive isotope detected from interstellar space. In 1979, the High Energy Astronomical Observatory satellite observed the 1.809-MeV gamma-ray that is emitted during $^{26}Al$'s decay (*1*). Since then, experiments aboard the Compton Gamma-Ray Observatory have established from the observed gamma-ray flux that a steady-state abundance of about 3 solar masses ($M_\odot$) exists in our galaxy's interstellar medium today (*2*). These observations show that element formation has occurred over the past million years in the galaxy and provide information about recent rates of star formation and supernova occurrence. Aluminum-26 is synthesized by proton capture on $^{25}Mg$ in a variety of stellar environments (*3*), but the observed spatial distribution of $^{26}Al$ in the galaxy strongly suggests that massive stars are the dominant source (*4*). The recently inferred simultaneous presence of $^{26}Al$ and $^{44}Ti$ in a supernova remnant in Vela suggests that both radioactive isotopes were synthesized in the explosion of the same massive star (*5*). If confirmed, this observation would lend further support to the idea that the $^{26}Al$ originates from massive stars. From these arguments and the observed $^{26}Al$ abundance, one can infer that over the past million years roughly 5 $M_\odot$ of interstellar gas has been turned into stars each year and that about once every 30 years a massive star has exploded (*6*).

Aluminum-26 may also provide insights into the early history of our solar system. Millimeter-sized calcium- and aluminum-rich inclusions (CAIs) in certain meteorites are solids formed extremely early in the solar nebula and are among the most primitive objects in the solar system. Many contain excess $^{26}Mg$ compared with the average concentration in the solar system. Magnesium-26 is the daughter of $^{26}Al$, and the excess $^{26}Mg$ correlates with the concentration of aluminum in these CAIs. From these observations, it can be inferred that $^{26}Al$ was present at an abundance of $^{26}Al/^{27}Al \approx 5 \times 10^{-5}$, the so-called "canonical" level (*7*), when the object condensed. Two outstanding puzzles remain regarding $^{26}Al$ in the early solar system: Why was its concentration so high? And was it homogeneously distributed? How well $^{26}Al$ can be used as an hourglass for studying the early solar system's history depends on the answers to these two questions.

From the inferred $^{26}Al/^{27}Al$ value in the CAIs, one would expect an abundance of about 30 $M_\odot$ in the current steady-state interstellar medium, about 10 times that actually observed from the gamma-ray measurements. Furthermore, $^{26}Al$-rich supernova debris are typically not directly injected into molecular cloud cores where stars form but rather into hotter phases of the interstellar medium where it must mix into cloud cores on $10^8$-year time scales. When this is accounted for, the meteorites contain about four orders of magnitude too much $^{26}Al$ compared with expectations for a steady-state interstellar medium (*8*). This implies that the live $^{26}Al$ in the early solar system was not a residue of ongoing, continuous galactic nucleotide synthesis but rather was produced shortly before CAI formation. A massive star may have exploded just before the sun's birth (perhaps triggering the collapse of the solar cloud) and injected the $^{26}Al$-rich debris into the solar nebula (*9*). Alternatively, energetic particles from the ambient molecular cloud (*10*) or from the protosun itself (*11*) could have synthesized $^{26}Al$ locally in the solar nebula. Both possibilities receive ongoing scrutiny. However, the recently detected excesses of $^{41}K$ in samples from the early solar system and their correlation with calcium content suggest that the even shorter lived $^{41}Ca$ ($\tau_{1/2} = 1.0 \times 10^5$ years) was also alive in the early system (*12*). The correlation of live $^{41}Ca$ with live $^{26}Al$ in CAIs tends to favor the massive-star injection scenario (*13*).

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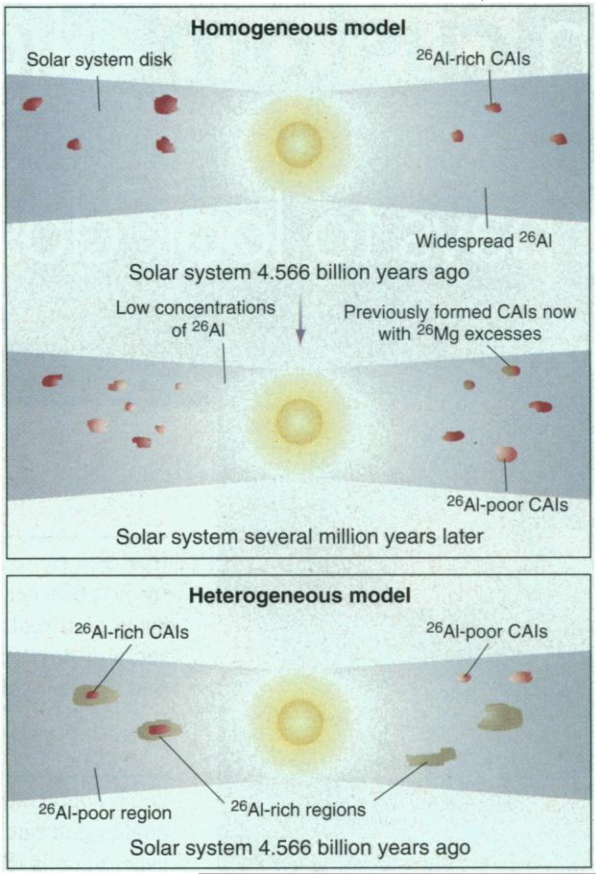
Other CAIs show little or no excess $^{26}$Mg (*14*). These primitive objects may have formed several million years after the more common CAIs, by which time the $^{26}$Al had largely decayed. Alternatively, the $^{26}$Al may have been heterogeneously distributed on a macroscopic scale; in this case, the CAIs could have formed at the same time, some in $^{26}$Al-rich regions and others in $^{26}$Al-poor ones (see the figure). The homogeneous and heterogeneous distribution models have very different implications for the early solar system. The homogeneous model requires the solar nebula to have persisted for several million years to allow formation of the $^{26}$Al-poor CAIs. In this scenario, some mechanism must have prevented the $^{26}$Al-rich CAIs from drifting into the protosun by gas drag (*15*). The alternative interpretation requires an explanation for the heterogeneous distribution of $^{26}$Al, which could have arisen from heterogeneous mixing of the massive-star debris into the solar cloud or from an inhomogeneous irradiation of the early solar system by energetic particles. An inhomogeneous distribution of $^{26}$Al may limit its usefulness as an hourglass.




**Aluminum-26 in the early solar system.** Two different pictures exist for the distribution of $^{26}$Al in the early solar system. In the homogeneous picture, CAIs with high concentrations of $^{26}$Al formed first **(top)** and CAIs with low concentrations of $^{26}$Al formed later after decay of most of the $^{26}$Al **(middle)** while the solar nebula persisted. Alternatively, both types of CAIs may have formed at the same time in a solar nebula with a heterogeneous distribution of $^{26}$Al **(bottom)**.

Several presentations at a recent conference addressed these issues (*16*). H. Vanhala and A. P. Boss (Carnegie Institution of Washington) presented hydrodynamical calculations that illustrated how material ejected by an exploding massive star might be mixed into a protosolar cloud by instabilities generated by the shock passage. B. Choi and collaborators (California Institute of Technology) measured $^{60}$Ni, the daughter nuclide of $^{60}$Fe, another short-lived radioactive isotope apparently alive in the early solar system, in CAIs showing excess $^{26}$Mg. The inferred $^{60}$Fe abundance was too low to be consistent with bulk injection from a massive star. This may be resolved, however, if not bulk supernova matter but rather only the $^{26}$Al-rich and $^{60}$Fe-poor outer layers were injected into the solar nebula (*17*). Y. Guan and collaborators (Smithsonian Institution and California Institute of Technology) measured $^{26}$Al in CAIs from enstatite chondrites, a different class of meteorites deriving from a different region of the solar system than the meteorites previously described. They found evidence for live $^{26}$Al at the canonical level, indicating that $^{26}$Al was widespread in the early solar system. Calculations presented by R. H. Nichols Jr. and co-workers (Washington University and Clemson University) showed that a heterogeneous distribution of $^{26}$Al arising from a late injection of bulk supernova matter would be accompanied by observable isotopic anomalies in stable isotopes. These anomalies are not seen, arguing against a heterogeneous $^{26}$Al distribution arising from injection of massive-star matter, although again injection of only the outer layers of the supernova debris is not ruled out. Finally, G. Srinavasan and colleagues (California Institute of Technology and Physical Research Laboratory, Ahmedabad, India) presented measurements of $^{26}$Mg in mineral samples from the differentiated meteorite Piplia Kalan that recently fell in India. They infer that $^{26}Al/^{27}Al \approx 10^{-6}$. Such a high concentration in a differentiated meteorite indicates that $^{26}$Al was the heat source that melted the parent body of this meteorite. Unfortunately, attempts to date Piplia Kalan with other radioactive species have not yet succeeded, and it is not yet possible to use this meteorite to establish a $^{26}$Al chronology.

Despite these advances, our understanding of $^{26}$Al in the early solar system remains murky. Some researchers have advanced views that are rather different from the current paradigms. One idea is that the $^{26}$Al-poor CAIs formed before the addition of $^{26}$Al to the solar system (*15*). According to another, $^{26}$Al was never live in the early solar system at all and the $^{26}$Mg excesses arose from fossil $^{26}$Mg in the interstellar dust grain precursors to the CAIs (*18*). These ideas lie somewhat outside the current mainstream, but they must be kept in mind. Aluminum-26 is an hourglass we can only see through darkly at present, but it is likely to be one of the major tools for understanding the solar system's early history.

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