solar wind nitrogen: mechanisms for isotopic evolution
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since the original discovery of a time-dependent variation in the isotopic
composition of implanted n in lunar soils (1,2), a number of additional lines of
evidence have been presented (3,4), consistent with the idea that this variation
results from a secular change in composition of the solar wind reservoir (1).
however, the mechanism responsible for this change has not been convincingly
identified, so we review here the status of various possibilities suggested so
far, in light of present experimental results. in view of what appear to be
considerable uncertainties in knowledge of the appropriate solar physics, we
focus upon processes capable of yielding a specific observational prediction.

summary of nitrogen isotope systematics in the regolith
[a] the $\delta^{15}N$ values of individual soil samples cover a range of about 200%,
and show a strong negative correlation with their cosmic ray exposure ages
derived from contents of $^{21}Ne$ (1,3), figure 1.
[b] the lower depths of the apollo 15 deep drill string, deposited more than
450 my ago (5), are marked by low $\delta^{15}N$ values, consistent with the rate of
change inferred from [a] above (1,6).
[c] values of $\delta^{15}N$ for grain size separates increase with grain size (3).
[d] stepwise heating experiments reveal two non-indigenous n components. one is
isotopically heavy, released at relatively low temperatures: apparently
recently implanted solar wind. the second, released at higher temperatures,
is isotopically light: apparently ancient solar wind buried within
agglutinates (3).
[e] partial fluorination removes an isotopically heavy surficial component:
apparently recently implanted solar wind (4).

these data may all be interpreted in terms of n
implanted from a source which has increased in
$\delta^{15}N$ by about 20% in a time period of the order of
10^9 years. identification of this source with the
solar wind is most plausible although the presence
of a parentless atmospheric component has also
been suggested (3). the observed variations cannot
be attributed to reactions on the lunar surface
because $\delta^{15}N$ does not correlate with actual
surface exposure and the observed trend is in the
wrong sense, and of excessive magnitude, for an
origin by spallation in the regolith (1,3). we
therefore concentrate here on processes capable
potentially of affecting the solar wind reservoir.
our approach will be to define each process as
quantitatively as possible using observed n
systematics and then to calculate analogous
variations expected in other elements or isotopes,
concentrating on species which might be analysable
in the sun or the solar wind.

mass fractionation

preferential acceleration of light species into the solar wind may enrich
figure 1 courtesy science 188, 162 (1975) american association for the
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the reservoir in heavy species with time. Assuming a mass dependence given by \( Z^2/[2A-Z-1] \) (7), the associated fractionation factor for mass 14 with respect to mass 15, taking \( Z = 4 + 5 \) (7), would be 1.091. If reservoir enrichment follows the Rayleigh distillation law, the observed 20% increase in \( \delta^{15}N \) requires 89% of the N in the reservoir to have been lost into the wind. This would have led also to a corresponding increase of 24% in \( \delta^{13}C \) whereas, not only is there no systematic variation of \( \delta^{13}C \) with \( \delta^{15}N \) (1), but the observed variability in \( \delta^{13}C \) among lunar soils is only about 2%. Similarly, an increase of about 90% would be expected in the \( ^{132}Xe/^{84}Kr \) ratio in the solar wind over a comparable period, whereas this ratio actually decreases by about 30% from bottom to top of both the Apollo 15 and 16 deep drill strings (8). Mass fractionation therefore fails the available observational tests.

SPALLATION

If spallation of \( ^{16}O \) by high energy protons in the surface regions of the sun is responsible for increasing \( \delta^{15}N \) in the solar wind (1), comparable spallation of \( ^{12}C \) and \( ^{4}He \) should also have occurred. As the three cross sections are approximately equal (9), the reaction yields may be directly compared. A 20% increase in \( \delta^{15}N \) requires a spallation yield of \( 1.24 \times 10^{-6} \) from \( ^{16}O \). A corresponding yield from \( ^{12}C \) would increase the ratio \( ^{11}B/H \) by \( 4.6 \times 10^{-7} \), whereas the observed spectroscopic upper limit for \( B/H \) is \( 1.2 \times 10^{-6} \) (10). This observation could be compatible with the spallation model if B were being simultaneously depleted by thermonuclear burning in the sun, as is invoked to explain the discrepancy between the solar photospheric abundance and the primordial Solar System value inferred from carbonaceous meteorites, \( B/H \approx 10^{-8} \) (11). Such burning would not necessarily deplete \( ^{15}N \) (12) but would certainly deplete Be far below its observed photospheric abundance, unless that spectroscopic measurement is in error (11). The \( ^{3}He/^{4}He \) ratio in the solar wind does not constitute a test of the hypothesis because the observed value is greater than the expected spallation product.

An additional constraint on solar spallation may be supplied by the observed flux of nuclear gamma rays (13,14). Such gamma rays, produced during spallation, would be observed at the earth and preliminary calculations indicate that a spallation rate adequate to produce the observed increase in \( \delta^{15}N \) would require a photon flux > \( 10^4 \) times either the quiet time upper limit or the time-averaged flux from flares, a discrepancy pointed out also by Fireman et al. (15). Spallation therefore fails the tests.

NEUTRON CAPTURE

Neutron capture on \( ^{14}N \) produces \( ^{15}N \) with a cross section which is a factor of 22 less than that for (n,p) production of \( ^{14}C \), evidence for which has been found in the solar wind (16). Given a suitable neutron flux this reaction could take place at any depth in the sun where \( ^{15}N \) is stable. Consequently the nuclear gamma ray data do not serve as a constraint on this process. However, a neutron flux capable of increasing \( \delta^{15}N \) by 20% would also have produced an 80% decrease in \( ^{12}Xe \) and a 55% depletion in \( ^{131}Xe \) (with corresponding increase in \( ^{132}Xe \)). In fact, the proportions of these isotopes in surface correlated trapped solar wind are within 2% of those in AVCC Xe (17), thus placing severe limits on the neutron flux experienced by material in the solar wind reservoir. Neutron capture also fails the observational tests.
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MIXTURE OF SOLAR WIND WITH AN ISOTOPICALLY LIGHT COMPONENT

It is possible that the $\delta^{15}\text{N} - ^{21}\text{Ne}$ relationship represents a mixing line between solar wind ($\delta^{15}\text{N} \approx +110$) and a light component $X$. Two possibilities have been advanced for the identity of $X$:

[a] $X$ is indigenous lunar N outgassed from the interior in quantities diminishing with time, analogously to parentless $^{40}\text{Ar}$ (3). The isotopic composition of indigenous lunar N has not yet been clearly defined; a $\delta$ value below $-100$ is required to satisfy the observations and this would imply either correspondingly light N in the primitive sun (leading to the same questions considered above) or heterogeneity in the nebula (a 20% difference between the solar and lunar formation locations, for which there is no evidence).

[b] $X$ is identified with nova grains accreted by the moon (18). This implies either a flux of such grains which decreased linearly with time or that apparently cosmogenic $^{21}\text{Ne}$ in lunar soils was actually of nova origin. The latter alternative cannot be reconciled with the agreement between $^{21}\text{Ne}$ ages and other cosmogenic dating schemes. These models are not yet rigorously testable.

ACCRETION OF INTERSTELLAR MATERIAL

In general, interpretations based upon contamination of either the lunar surface or the solar wind reservoir by interstellar material suffer from the low flux of such material, $\sim 10^{-3}$ times that of the solar wind at 1 AU, and/or dilution within the relatively large mass of the solar convective zone. Otherwise such models are not yet testable.

CONCLUSION

All quantitative models proposed so far are in serious conflict with some observational evidence. Of the remaining possibilities, the model involving parentless light N (3) seems to pose the fewest problems but supportive evidence is lacking and it strictly survives only by default at this time.

REFERENCES