nant anthropogenically produced aerosols, sulfate aerosols, are conventionally believed to cool the atmosphere by reflecting sunlight (the direct effect) and by making clouds more reflective (the indirect effect). Recent observational and modeling studies have indicated that aerosols with substantial black carbon (soot) content (see the figure) offset some of this cooling (*7*). The global magnitudes of these effects are uncertain, however, adding risk to any strategy that relies on modifying aerosols.

Haze isn't cool. This photo from the recent Indian Ocean Experiment (INDOEX) shows polluted air masses. It has recently been shown (*7*) that soot-containing aerosol pollution can reduce cloud cover, thus offsetting the expected aerosol-induced cooling of the atmosphere substantially. The magnitude of the effect is, however, uncertain.

CREDIT: FROM (7)

Hansen *et al.* propose to reduce the black carbon content of aerosols in order to increase the cooling effect of aerosols. In the absence of changes in net sulfur dioxide (SO_2) emissions, less black carbon as a result of pollution controls would, indeed, lead to increased cooling. The technology for reducing soot emissions is widespread, and it is reasonable to assume that future efforts to control local air pollution will result in a decrease in these emissions. Efforts to control SO_2 and other aerosol precursor compounds will, however, also be taken. It is extremely unlikely that reduced soot emissions would, or even could, occur in isolation.

Furthermore, any strategy that limits CO_2 emissions will limit fossil fuel use and will therefore also reduce emissions of aerosol precursors that usually accompany fossil fuel use. This effect is demonstrated in the SRES B1 scenarios, in which CO_2 emissions increase relatively modestly over the next 50 years and, in all but one scenario, global SO_2 emissions fall. Adding a CO_2 mitigation policy to meet the 1 W/m^2 target is likely to decrease SO_2 emissions even further. Such a decrease in SO_2 emissions is most likely to result in a net decrease in aerosol cooling. To convert this to an increase in cooling, a nearly global removal of soot would be required (*8*), and even then the strategy would only work if the soot forcing effect is strong (its magnitude is highly uncertain).

Some SRES scenarios have constant or increasing emissions of SO_2 through 2050, which might allow soot reductions to cause an increased cooling effect. These scenarios generally have, however, CO_2 emissions that are much higher than those required to meet a 1 W/m^2 target. They are therefore unsuitable for the Hansen *et al.* strategy.

Even if selective reduction of the soot component of aerosol forcing were practical, it would only provide temporary relief (*9*). This approach does not address the long-term effects of greenhouse gas emissions. SO_2 emissions decline from 2050 to 2100 in all SRES scenarios. By the last half of this century, radiative forcing will be increasingly dominated by long-lived greenhouse gases such as CO_2 and nitrous oxide. In addition, much of the infrastructure related to the emissions of these gases has a long lifetime, and plans to stabilize radiative forcing by the end of the next century must be well in place by 2050. A policy that relies on a temporary aerosol cooling offset, even if successful, is likely to shortchange the longer term goal.

The goal of the FCCC is the "stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system" (*10*). Much of the ongoing discussion has therefore focused on the long term. An additional focus on limiting shorter term increases in radiative forcing, as suggested by Hansen *et al.*, should also be considered, particularly if further research shows that increases in the rate of climate change are likely (*5*). Reducing emissions that lead to local air pollution may, indeed, help contribute to reducing climate forcing. Pollution controls, however, rarely reduce a single constituent, and as discussed above, this will limit the overall magnitude of any pollution-control–derived forcing reduction. Economic considerations and the nature of the climate target can change the emphasis on CO_2 relative to other radiatively important substances (*11*), but the primary focus must remain on CO_2.

References and Notes

1. J. Hansen *et al.*, *Proc. Natl. Acad. Sci. U.S.A.* **97**, 9875 (2000).
2. Stated by Hansen *et al.* as keeping the CO_2 concentration growth rate "about the same as in the past two decades." Note that a constant rate of concentration growth requires a decreasing rate of emissions increase.
3. See www.cop4.org/kp/kp.html
4. N. Nakicenovic, R. Swart, Eds., *Special Report on Emissions Scenarios* (Cambridge Univ. Press, Cambridge, 2000).
5. S. J. Smith, N. Nakicenovic, T. M. L Wigley, in preparation.
6. Possible increases (decreases) in tropospheric ozone forcing would make this target more (less) difficult to reach. Ozone forcing changes have not been included in our forcing calculations (*5*).
7. A. S. Ackerman *et al.*, *Science* **288**, 1042 (2000).
8. If emissions are "clean" in some regions and "dirty" in others, then net global aerosol properties will be much as they are at present. If emissions decrease, forcing will decrease.
9. A. Grübler, *Mitigation Adapt. Strategies Global Change* **3**, 383 (1998).
10. See article 2 in www.unfccc.de/
11. A. S. Manne, R. G. Richels, in preparation.

12. The authors would like to thank H. Pitcher and M. MacCracken for helpful comments.

PERSPECTIVES: PLANETARY SCIENCE

Nitrogen on the Moon

Richard H. Becker

A continuous stream of atoms and electrons flows from the sun's surface into the solar system. This solar wind has left its signature in the lunar "soils" (the residue of rocks broken down by impacting meteorites) that cover most of the moon's surface. The solar wind has implanted itself into the surfaces of individual soil grains to depths of tens of nanometers. For elements such as carbon, nitrogen, and the noble gases, whose normal abundance is very low in lunar rocks, the solar component can be distinguished from the indigenous lunar contribution, allowing insights into the elemental and isotopic composition of the solar wind over time.

The lunar surface is thus a potential source of information on changes in the sun over its lifetime. For the element nitrogen, however, the lunar record may reflect more than just solar processes. Almost from the first soil analyses for nitrogen, we have known that ${}^{14}N/{}^{36}Ar$ in lunar soils is elevated by a factor of about 10 relative to the sun, that ${}^{15}N/{}^{14}N$ ratios vary from sample to sample by more than 30%, and that this isotopic variation is related to the time when the nitrogen was introduced to the moon (*1*). Understanding these observations could shed light on lunar surface processes, solar system history, or the origin of the material from which the solar system formed. Nevertheless, after some 25 years we are still trying to make sense of them. The measurement of elemental and isotopic depth profiles in individual grains of lunar soil, as reported by Hashizume *et al.* on page 1142 of this issue (*2*), may bring us closer to an understanding.

Initially, the isotopic ratios seemed

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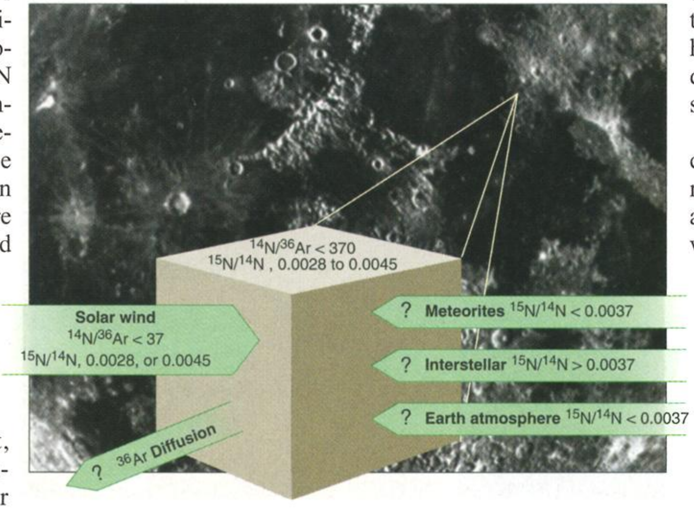
straightforward to explain. Early measurements were done on unseparated or grain-size separated soils. Such samples are full of particles that have experienced meteorite impacts, which heat and partially or totally melt some grains. Relative amounts of ^{36}Ar, ^{84}Kr, and ^{132}Xe in the soils are different from accepted solar ratios, with the lighter elements depleted. This suggests a mass-related loss of noble gases, as might occur by diffusion from the heated grains. In contrast, nitrogen may undergo little or no loss upon heating, because it can form chemical bonds in minerals. Preferential loss of noble gases in conjunction with meteorite impacts could therefore explain the overabundance of ^{14}N. Variations in ^{15}N/^{14}N were believed to reflect either real changes in this ratio in the outer layers of the sun over time or addition into the soils of nonsolar nitrogen with a very different ^{15}N/^{14}N than solar wind. Residues from impacting meteorites (*3*), nitrogen degassed from the interior of the moon (*4*), or transfer of nitrogen from the top of Earth's atmosphere to the moon (*5*) were considered potential sources of this second nitrogen component (see the figure). Such a nonsolar nitrogen component would also contribute to the enhanced ^{14}N/^{36}Ar ratio.

These explanations did not, however, fare well on detailed examination. Geiss and Bochsler (*6*) evaluated proposals relating to changes in the ^{15}N/^{14}N in the sun itself and concluded that none of them were adequate. More recently, Wieler and Baur (*7*) presented evidence that the differences in ^{36}Ar/^{84}Kr/^{132}Xe ratios between accepted solar values and those in lunar soils are unlikely to result from diffusive losses on the moon but are instead a result of processes occurring at the solar surface. The overall enhancement of ^{14}N to ^{36}Ar in lunar soils is therefore unlikely to result from a 90% loss of argon from the soils, although such losses might be invoked in individual cases. This pointed to a nonsolar nitrogen component in the soils, but mixing models involving addition of a second nitrogen component to bulk soils were found to be inconsistent with known correlations between nitrogen and other soil parameters (*1*, *8*). In addition, analyses of samples containing only pure mineral grains and not the heavily processed and melted particles found in soils showed that any nonsolar nitrogen component was not simply present as an additional kind of particle sprinkled into the mix of grains. Instead, it had to be present on or within the lunar mineral grains themselves. Thus, until just a few years ago, no consensus explanation existed for the observations on nitrogen in lunar soils.

The advent of techniques that can analyze individual mineral grains has improved our understanding of the situation considerably. Measurements of total Ar, Kr, and Xe abundance in single grains (*9*) support the conclusion (*7*) that these noble gases are not substantially lost from lunar minerals. Combined nitrogen and ^{36}Ar measurements from individual grains (*10*) strongly suggest that two nitrogen components are present in every soil grain exposed to the solar wind, one associated with the ^{36}Ar and therefore of solar origin and a second of some other origin. Solar nitrogen amounts vary greatly from grain to grain, reflecting the amount of time they were directly exposed to the sun. In contrast, the second component is fairly constant in amount and is the dominant component in all grains. This latter component appears to be associated with grain surfaces, both from the depth profiles of Hashizume *et al.* (*2*) and because the amount of this component is related to the surface area of the grains (*10*). Parameters determined for total soils (such as ^{14}N/^{36}Ar ratios) average out the properties of widely divergent individual grains, and thus the arguments made earlier against two-component mixing based on bulk soils (*1*, *8*) may actually not apply.



Something for everyone. Mineral grains from the lunar surface contain nitrogen and argon implanted into the grain surfaces by exposure to the solar wind. The lunar N/Ar ratio is much larger than that expected for solar wind, and the lunar nitrogen isotopic ratio is highly variable. These observations have been variously explained as due to diffusive loss of solar wind argon, addition of nonsolar nitrogen from several potential sources to the lunar surface, changes in the solar nitrogen isotopic composition over time, or some combination thereof.

PHOTO: UCO/LICK OBSERVATORY

So where are we now? Enhanced ^{14}N/^{36}Ar ratios appear to be due to the presence of a major nonsolar, surface-situated, nitrogen component in lunar mineral grains. Its origin and that of the variation in ^{15}N/^{14}N ratio remain to be explained. Hashizume *et al.* (*2*) suggest residual interstellar matter with high ^{15}N/^{14}N added to a solar wind with low ^{15}N/^{14}N ratio. Geiss and Bochsler (*6*) suggested just the reverse, that is, high ^{15}N/^{14}N solar wind admixed with a component of low ^{15}N/^{14}N. Neither of these take full account of the spacecraft measurements of the solar wind mentioned in (*2*). These indicate that today's solar wind has relatively high ^{15}N/^{14}N, whereas Jupiter's atmosphere, which may represent the original solar ratio, has low ^{15}N/^{14}N. Uncertainties for both results are large, however, and assumptions are required to get from the Jupiter result to a solar value.

A NASA Discovery mission, called Genesis, planned for the near future, is expected to collect and return a sample of solar wind for laboratory analysis of, among other things, ^{15}N/^{14}N with much higher precision than that obtained by the SOHO spacecraft. This should nail down the present-day value and thus eliminate some of the possible explanations. Further single-grain studies, including depth profiling as done by Hashizume *et al.* (*2*) but with the addition of ^{36}Ar to act as a tracer for the solar wind component, are needed to expand the observations in (*2*). Comparisons between directly comparable grains (such as of the same mineral) from soils with very different bulk ^{15}N/^{14}N ratios are needed. And we need suggestions as to how a nonsolar nitrogen component may get taken up on lunar soil grains in what appears to be a uniform and surface-area–related manner, independent of the duration of direct exposure of the grains to the sun.

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