ATMOSPHERIC SCIENCE

Whither Geoengineering?

Costs, benefits, and harms associated with geoengineering must be assessed before it is used to mitigate climate change.

Alan Robock

According to the Intergovernmental Panel on Climate Change (IPCC) (*1*), global warming will soon have severe consequences for our planet. The IPCC also estimates (*2*) that mitigation would only cost ~0.1% of the global gross national product per year for the next 30 years, a price far smaller than the damage that would occur. As a potential route to mitigation, the old idea of "geoengineering" has gotten much attention in the last 2 years (*3*, *4*). On page 1201 of this issue, Tilmes *et al.* (*5*) quantify the effects of one geoengineering approach—the introduction of additional aerosols into Earth's stratosphere, akin to a volcanic eruption—on high-latitude stratospheric ozone concentrations.

A polar stratospheric cloud over McMurdo, Antarctica, on 24 August 2004. These clouds cause ozone depletion every spring because of anthropogenic chlorine in the stratosphere. The ozone hole is expected to disappear by the middle of this century, but with geoengineering, the Antarctic ozone hole would continue to form for another 30 to 70 years.

Geoengineering involves trying to reduce the amount of sunlight reaching Earth's surface to compensate for the additional long-wave infrared radiation from greenhouse gases, thereby reducing or reversing global warming (*6*). Even if it works, there are problems with this approach (*7*). If perceived to be a possible remedy for global warming, it would reduce societal pressure to reduce greenhouse gas emissions. It could reduce overall precipitation, particularly Asian and African summer monsoon rainfall, threatening the food supply of billions. It would allow continued ocean acidification, because some of the carbon dioxide humans put into the atmosphere continues to accumulate in the ocean. Weather modification could be used as a weapon (*8*), thus violating the 1977 U.N. Convention on the Prohibition of Military or Any Other Hostile Use of Environmental Modification Techniques. There would be rapid warming if geoengineering stopped suddenly. If geoengineering worked, whose hand would be on the thermostat? How could the world agree on an optimal climate?

Nevertheless, for some schemes, the benefits may outweigh the problems, especially if used on a temporary basis. To date, only some schemes have been investigated in detail. Furthermore, proponents of geoengineering, especially the fossil fuel industry, will continue to push for its use.

Sunshades in orbit around Earth (*9*) or cloud seeding to brighten them (*10*) have been proposed, but most geoengineering ideas focus on emulating explosive volcanic eruptions by injecting SO_2 or H_2S into the stratosphere, producing a sulfuric acid cloud to scatter solar radiation back to space and cool the planet. Deciding whether this is a good idea or not requires detailed analysis of the costs, benefits, and harm to the planet that such a strategy would entail, and comparison to the same metrics for mitigation and sequestration. Given the need for rapid mitigation, these ideas need rapid and thorough investigation.

It has been suggested (*3*, *4*) that the cooling of the global climate for a couple years after large volcanic eruptions—like the 1991 Mount Pinatubo eruption—serves as an innocuous model for what humans could do by creating a permanent stratospheric aerosol layer. However, volcanic eruptions actually serve as a warning about geoengineering: They produce drought (*11*), hazy skies, much less direct solar radiation for use as solar power, and ozone depletion (*12*).

We now have an ozone hole over Antarctica every spring because the polar stratospheric clouds that form there (see the figure) serve as surfaces for heterogeneous chemistry that releases chlorine, which then catalytically destroys ozone. Polar stratospheric clouds only form when the temperature falls below ~195 K, but additional sulfate aerosols provided by geoengineering or volcanic eruptions alter these temperature restrictions and provide more surface area for the chemistry, allowing more chlorine to be activated and more ozone to be destroyed.

Advocates of geoengineering suggest that this ozone problem would not be important, because the stratospheric concentration of chlorine is slowly decreasing as a result of global environmental agreements (*13*). However, Tilmes *et al.* show that even with the projected chlorine declines, ozone depletion (and increased ultraviolet flux) would be prolonged for decades by geoengineering of the stratospheric sulfate layer. In their model, the effects would occur every spring in the Southern Hemisphere and in most springs in the warmer Northern Hemisphere. The presence of sulfate aerosols would raise the temperature needed for chlorine activation over 200 K, expanding both vertically and horizontally the regions of polar ozone depletion.

A U.S. Department of Energy white paper (*14*) in October 2001 recommended a $13 million/year national geoengineering research effort, but the paper was never released. According to the paper, "any effort to deliberately moderate or ameliorate threats that may arise or become more likely as a result of climate change should be undertaken only in extraordinary circumstances.... In view of the risk of significant consequences to society and the environment from either inaction or

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poorly understood actions, research should be initiated now to examine possible options to moderate adverse climate threats; to ensure that these options are effective, affordable, reversible and sustainable."

It is not too late to make up for lost time, but further delay must be avoided. A research program, more generously funded than that proposed in 2001, supported by the U.S. federal government with international cooperation, will allow us to compare the efficacy, costs, and consequences of the various options of responding to global warming—mitigation, sequestration, geoengineering, or doing nothing—so that an informed public can agree on the best courses of action.

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ASTRONOMY

A Blast from the Past

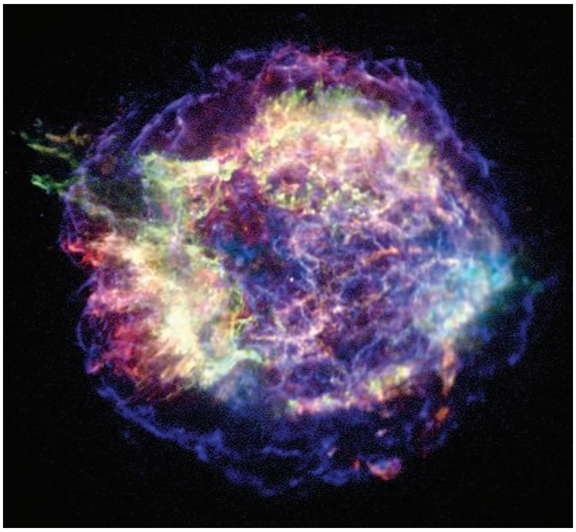
Echoes of light, reflections from nearby gas and dust clouds, can be used to reconstruct past astronomical events.

Andrew C. Fabian

Have you ever wanted to view an event that happened many years ago? Most of the light from that event is still traveling through space and can, in principle, be reflected back to us to reconstruct the event. This is, of course, completely impractical for events that occur on a human scale, but when a star explodes as a supernova, so much light is emitted that it may be possible to see a delayed reflection from surrounding dust clouds. On page 1195 of this issue, Krause *et al*. (*1*) report their observations of a light echo for the outburst of Cassiopeia A (Cas A), which is the most recent nearby supernova known to have occurred in our Galaxy.

The remnant of Cas A was first discovered in 1947 and identified optically in 1950. From its observed expansion, it can be deduced that the explosion itself would have occurred around 1680, as viewed from Earth. A recent x-ray image of the remnant is shown in the figure.

More recently, infrared images made with the Spitzer Space Telescope revealed moving light echoes around Cas A 4 years ago (*2*). These echoes were monitored last year with the Calar Alto optical telescope in Spain, and a spectrum of a particularly bright patch was taken by the Subaru telescope in Hawaii. The echo spectrum clearly shows light from the supernova. When a star of 10 to 20 solar masses explodes, an energy equivalent to about 1% of the mass of the Sun is turned into kinetic energy of the stellar envelope, which then expands into space at velocities of 10,000 km/s or more. The spectrum shows emission and absorption lines Doppler-broadened by such large velocities. The presence of hydrogen lines in the spectrum places it in the category of a type II supernova, which results from collapse of the core of a massive star when it runs out of fuel, as was long suspected from the properties of the still-expanding remnant. The spectrum is remarkably similar to that of supernova 1993J (SN 1993J), a type IIb supernova seen (in 1993) in the nearby galaxy M81.



Supernova remnant. An image of the Cas A remnant taken by the Chandra X-ray Observatory (CXC).

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Light echoes also have recently been seen from SN 1993J (*3*), and from other supernovae in our satellite galaxy, the Large Magellanic Cloud (*4*), including the famous SN 1987A (*5*), which is the only supernova to have been seen with the naked eye since the invention of the telescope more than 400 years ago. Van den Bergh (*6*) in 1966 had tried to look for an echo around Cas A. However, we now know that it was much too faint to be seen with the photographic plates available at that time.

The light echo spectrum from Cas A is notable primarily because Cas A is a type IIb supernova and its remnant has been so well studied due to its proximity and youth. We can assume (*7*) that Cas A was a red giant before it exploded, and that it probably had a binary companion at some stage. The progenitor of SN 1993J was predicted to have been a member of a binary, and a massive star consistent with a companion remains at the site (*8*). There is no such stellar companion remaining at the position of Cas A, so it possibly spiraled into the progenitor some time before the explosion. A faint nonvariable pointlike x-ray source has been found (*9*) close to the center of the remnant and is probably a neutron star.

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