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Leads and Lags at the End of the Last Ice Age

Edward J. Brook

Science **339**, 1042 (2013);
DOI: 10.1126/science.1234239

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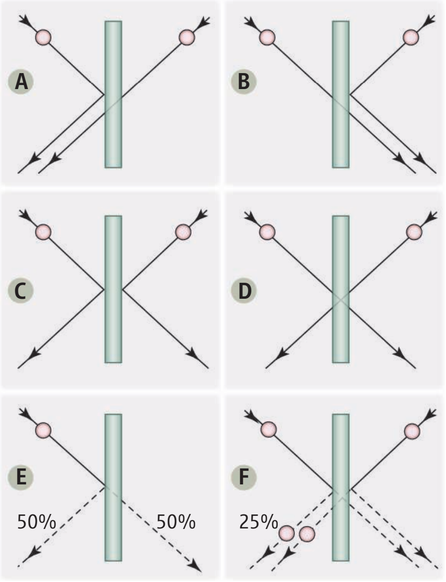

To bunch or not to bunch. Indistinguishable quantum particles incident from left and right sides of a 50% beam splitter can scatter in four ways. The symmetry of the wave function determines the outcome. For bosons, only (**A**) and (**B**) are possible (causing "bunching"), while for fermions only (**C**) and (**D**) are possible (causing "antibunching"). For comparison, (**E**) shows the random partitioning of particles incident on one input alone, and (**F**) illustrates the partitioning of two input beams of distinguishable particles. For example, for distinguishable bosons, two bosons exit with a probability of 25%, whereas indistinguishable bosons would show a twice-as-high probability of 50% for the same process.

ity should occur equally if the transmission and reflection probabilities were adjusted to 50%. However, fermions and bosons are not independent because they must obey symmetry rules. Bosons exclusively choose (A) and (B), causing them to bunch together to the same side, whereas fermions can only choose (C) and (D) and avoid each other—they antibunch.

In the optical HOM experiment, if the photons are distinguishable, they partition independently at the beam splitter (outcome F in the figure). In the electronic HOM experiment, Bocquillon *et al*. measured the noise in one of the output channels. If two indistinguishable electrons collided at the same time at the beam splitter, the noise was suppressed because both states were fully occupied without any randomness. If the two incident electrons appeared at different times at the beam splitter, they would be independent and randomly partitioned, resulting in noise. The noise suppression at zero time delay between the two electron wave packets confirmed the formation of a two-particle coherent fermionic state.

Two-particle interference in electronic devices have been studied before, exploiting two sources with a single beam splitter (*11*) and an impressive double Mach-Zehnder interferometer (*12*). The experiment by Bocquillon *et al*. comes much closer to a state-of-the-art quantum-optics experiment as it is realized in an electronic device that uses single-electron sources (*13*). In these sources, electrons can be launched on demand and with a predetermined time delay for tuning the wave-function overlap.

Unlike photons, electrons are charged particles that strongly interact. Hence, two-particle interference experiments may shed new light on the dephasing problem of electronic quantum states in quantum computing. Edge states also exist in the fractional quantum Hall state, which hosts quasiparticles with statistics distinct from those for both fermions and bosons. Recently, evidence for Majorana-like particles have been found in nanoelectronic devices (*14*), so it may be possible to probe their scattering and test their non-Abelian statistics. Less demanding, but still very exciting, is the interaction of the quasiparticle launched by the single-electron source with the "vacuum state," which for an electron system is not "empty" but a filled Fermi sea. Finally, because the electron source used by Bocquillon *et al*. provides an alternating current, it launches an electron at one instance and then a hole half a period later, which should allow the study of the interactions of electrons and holes that originate from different sources.

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10.1126/science.1234199

ATMOSPHERE

Leads and Lags at the End of the Last Ice Age

Edward J. Brook

Carbon dioxide concentrations and Antarctic temperatures were tightly coupled during the last deglaciation.

Over the course of Earth history it is generally believed that atmospheric carbon dioxide (CO_2) and climate are closely coupled (*1*). The most direct evidence comes from polar ice cores. Snow falling in Antarctica and Greenland gradually compacts to form solid ice and trap air. Polar ice also records past temperatures in the ratio of heavy to light isotopes in the water molecule. Ice core analyses have shown that Antarctic temperature and atmospheric CO_2 concentrations are highly correlated over the large-scale climate cycles of the past 800,000 years (*2*). But which came first? Does CO_2 drive climate cycles or is it a feedback in the system that contributes to warming? On page 1060 of this issue, Parrenin *et al*. (*3*) address this question in a study of CO_2 concentrations and Antarctic temperatures during the last deglaciation.

One reason that the answer to the above question is more complicated than it may seem is a peculiarity of air preservation in ice. Over the top 50 or 100 m of an ice sheet, the snowpack (firn) gradually becomes denser before it becomes solid ice containing air bubbles. Air diffuses rapidly through the firn, and the trapped air is therefore younger than the surrounding ice. In places with little snowfall, the age difference can be several thousand years. The age difference cannot be reconstructed perfectly, leading

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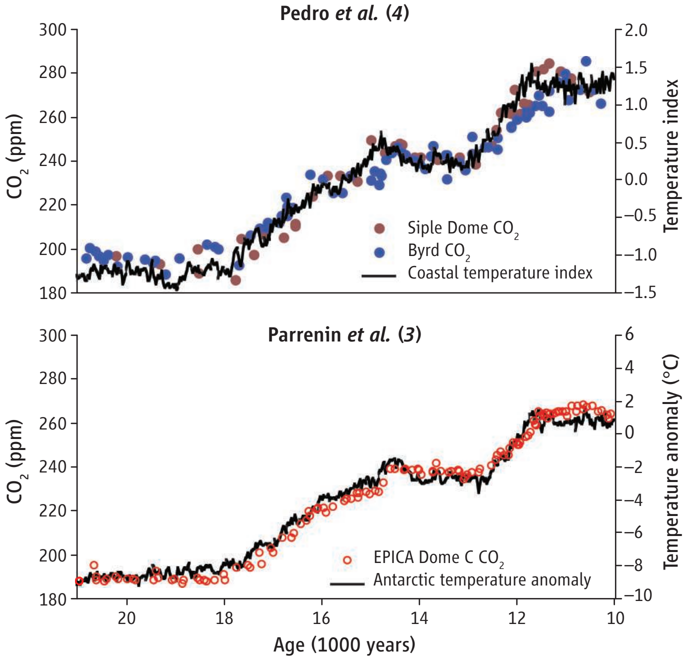
to uncertainty in the age of the air (containing the CO_2 record) relative to that of the ice (containing the climate record).

A second problem is related to the question itself. The global carbon cycle is an interlinked set of processes that both impact, and are impacted by, climate. For example, warming of the sea surface releases CO_2, and that increase contributes to further warming. Ocean circulation changes driven by changes in climate affect the amount of CO_2 sequestered in the deep ocean, in turn influencing surface temperature. It seems unlikely that a change in global climate would not influence CO_2 concentrations and vice versa. Seeking simple cause and effect is thus difficult.

A third issue is that different methods have been used to analyze the relationship between CO_2 concentrations and temperature over different time periods (*4*), making it difficult to compare results. And finally, ice core temperature records are mixtures of local and large-scale regional climate trends, and the large-scale importance of any one record, particularly over short time periods, is not clear. In contrast, CO_2 is well mixed in the atmosphere, and any ice core record should provide a global signal.

The best data capturing a major change in climate are for the last deglaciation, which took place between ~20,000 and ~10,000 years ago. The clearest CO_2 data set from that time period comes from the EPICA Dome C ice core. The original publication (*5*) reported that at the start of deglacial warming ~18,000 years ago, CO_2 lagged temperature change at Dome C by 800 ± 600 years, a figure that is widely cited. However, although the CO_2 data are excellent, the gas age–ice age difference at this site is very large, making the result—which depends on a model of firn compaction—uncertain.

Parrenin *et al*. address these concerns by using a different method to establish the gas age–ice age difference and by creating a composite record of Antarctic temperature from several ice cores from the Antarctic interior. They use the ratio of $^{15}N/^{14}N$ in nitrogen (N_2), which is enriched in firn due to gravitational settling (*6*). The enrichment depends on the depth of the firn column. Once this depth is determined from the nitrogen data, a simple model can predict the offset in depth between gas and coeval ice and the amount of time this represents. Parrenin *et al*. verify the approach with two independent estimates of the relationship between depth and age for EPICA Dome C. Their analysis indicates that CO_2 concentrations and Antarctic temperature were tightly coupled throughout the deglaciation, within a quoted uncertainty of less than 200 years (see the figure).



Lead and lag. Carbon dioxide concentrations and averages of temperature proxy records for last deglaciation, as compiled by Parrenin *et al*. (*3*) and Pedro *et al*. (*4*). Pedro *et al*. used existing CO_2 and temperature proxy data from coastal Antarctic cores and the temperature anomaly is presented in standard deviation units (the number of standard deviations from the mean of the record) to illustrate the average timing of temperature change. Parrenin *et al*.'s record is the average temperature anomaly for all the records they combine (in °C), relative to modern conditions. Using largely independent methods and data, both studies indicate a very tight coupling between regional Antarctic temperatures and CO_2.

Support for this conclusion comes from recent independent work of Pedro *et al*. (*4*). They used existing CO_2 and temperature proxies from coastal Antarctic cores with smaller gas age–ice age differences, but somewhat noisier CO_2 data and complex climate histories. They concluded that CO_2 lagged temperature by less than 400 years on average over the entire deglaciation and could not exclude the possibility of a slight lead.

In many ways, these results are not surprising, given the coupled nature of the carbon cycle and climate and the fact that oceanic processes around Antarctica probably play a key role in glacial-interglacial CO_2 dynamics (*7*). They are important, however, because they improve our understanding of when CO_2 changed with respect to temperature in the ice core record. Of course, questions remain. One is how to very precisely relate to the timing of CO_2 changes to climate changes recorded in other paleoclimate archives (*8*), given differences in dating methods. The time period around 18,000 years in the ice core record has been difficult to place firmly in an absolute chronology. New annually resolved ice cores and better correlations of ice cores from both hemispheres may alleviate this problem.

We also do not know whether the results can be generalized to other time periods. Previous work on older climate intervals supported a lead of temperature relative to CO_2 concentrations, but most, though not all (*9*), suffer from the same deficiencies that Parrenin *et al*. try to overcome. Analyzing older climate transitions will require high-resolution CO_2 records for those time periods, a laborious but probably worthwhile task, and development of better understanding of the transformation of snow to ice.

The ultimate question is what mechanisms influence both Antarctic climate and CO_2 concentrations on such intimate time scales. Many have been discussed, and many are plausible, including changes in CO_2 outgassing from the ocean due to changes in sea ice, changes in iron input to the ocean that influence CO_2 uptake by phytoplankton, and large-scale ocean circulation changes that cause release of CO_2 to the atmosphere. Deciding which are viable has proven difficult, but the new results of Parrenin *et al*. are a prerequisite for further understanding of the carbon cycle and climate.

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