internally, and how much of it is lost back into space? The key common source of energy in our solar system is the Sun, and this energy is distributed either through radiation or via the solar wind. Since the time of formation of our solar system, some energy has been stored internally in the planetary bodies as thermal, chemical, or rotational energy. Energy also reaches us from outside our solar system in the form of cosmic radiation, in particular gamma rays.

The high-energy ultraviolet portion of radiation from the Sun is absorbed in Earth's upper atmosphere by the principal gases nitrogen (N_2) and oxygen, both molecular and atomic (O_2, O). Most of the absorbed energy is thermally conducted to lower altitudes. Near 90 km (the mesopause region), CO_2 and other radiating molecules are abundant enough to emit a large portion of the energy back to space through infrared radiation. At high latitudes, energetic particles precipitating from the magnetosphere interact with the atmosphere, leading to substantial heating as well as spectacular auroral emissions. Electrical currents between the magnetosphere and the atmosphere can also heat the atmospheric gases at high latitudes, particularly during geomagnetic disturbances.

In essence, most of the physical processes that control Earth's energy balance are also acting on other planets. On Venus and Mars, the large abundances of CO_2 lead to effective radiative cooling of their upper atmospheres. The heating processes at auroral latitudes on Jupiter and Saturn may exceed solar heating rates because of the larger distances from the Sun. Another likely heat source on the gas giants is the transfer of energy from inside the planets to their outer atmospheres via waves.

The exploration of other bodies in our solar system also helps us understand our own planet far better. Cooling by CO_2, which dominates Venus and Mars, is also acting on Earth and turns out to be one of the keys to understanding the evolution of our atmosphere as well as climate change. Major uncertainties, however, pertain to Earth's CO_2 cooling rate, which is controlled by the excitation of CO_2 through collisions with atomic oxygen. It turns out that observing Mars or Venus simultaneously with Earth can help us better determine this rate, but such observations are challenging and have not been made until recently.

Now, analyses by Forbes et al. of the atmospheric drag on satellites orbiting Earth and Mars have yielded measurements of how variations in solar radiation intensity affect atmospheric densities. At any given altitude, heating of the atmosphere will result in an enhancement of densities and stronger atmospheric drag on a satellite. Measuring these drag variations allows derivation of atmospheric temperature changes, and thereby of the effects of solar forcing. Mars is found to be half as responsive as Earth to changes in solar forcing, but is estimated to be four to seven times as responsive as Venus. These numbers are corrected for distances from the Sun; thus, the differences are primarily due to the varying CO_2 cooling efficiencies, which have so far remained poorly understood. This study, in helping us to improve our knowledge of the CO_2 cooling efficiencies, is a prime example of how we can use other planets in our solar system as laboratories to better understand the complexity of our own atmosphere, and thereby improve our predictions of changes, including those due to anthropogenic effects.

Previous simultaneous observations of planets had focused on comparing solar forcing of the ionized portions of the atmospheres on Earth and Mars (2–4) and the propagation of interplanetary shocks through the solar system. Interplanetary shocks are triggered by violent solar eruptions and cause compression of magnetospheres around planets. Such compressions lead to increased levels of energetic particle precipitation into upper atmospheres, and thereby enhanced auroral brightness. Only recently, observations have followed an interplanetary shock as it propagated from the Sun to Earth, Jupiter, and Saturn and successively caused enhanced brightness of their aurorae (5), confirming the effects of solar forcing on planetary magnetic and plasma environments and atmospheres. These comparative space weather observations have highlighted important differences between the ionospheres and magnetospheres of planets, again helping us to better understand Earth and its space environment.

The examples illustrate that comparative studies of planets are far more effective than examining each body individually. Knowledge of Earth's atmosphere and environment helps us understand aspects of other planets, but we can only understand the evolution of our own atmosphere by studying those of other planets. Ultimately, the lessons learned within our solar system can also be applicable to the exploration of planets orbiting stars far from our solar system.

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BEHAVIOR

Align in the Sand

Daniel Grünbaum

Many animal species form large organized groups, but how information is shared within swarms, flocks, and heards is not clear. Studies of locust swarms reveal distinct transitions from disordered to ordered phases.

Large, coordinated animal groups such as swarms, herds, schools, and flocks are widespread phenomena that strongly affect many biological systems (1). High population densities often bring negative consequences (increased competition for resources, disease transmission, and attention from predators), but species that take advantage of dense populations to form organized groups may benefit by more effective foraging, reproduction, migration, and escape from predators. The analysis by Buhl et al. of coordinated movement in juvenile desert locusts on page 1402 of this issue presents the most detailed description yet of the behavioral mechanisms enabling social animals to form and maintain coherent, large-scale groups (2).

Locust plagues can contain 10^9 individuals and are among the most spectacular and consequential of animal aggregations (3). Seemingly spontaneous appearances of multitudes of hungry locusts, which fill the air and carpet the ground as each eats its own weight per day of natural and agricultural vegetation, have caused ecological, economic, and (after these locusts die and putrefy) epidemiological catastrophes of historic proportions (4). All of this devastation originates with a profound transition by immature, nonflying locusts from a relatively innocuous solitary phase, in which they actively avoid each other, to a behaviorally and physiologically distinct gregarious phase, in which they seek each other out (5). When this happens, the locusts form massive, coherent, and highly mobile foraging groups (see the figure). Desert locusts almost completely destroy plant material as they go, and they go a long way; migrations routinely carry these insects thousands of kilometers across Africa and have reached as far as Europe and the New World (6).

"The locusts have no King, yet all of them march in rank," observed an insightful ancient naturalist (7), capturing the enduring mystery of

The author is in the School of Oceanography, University of Washington, Seattle, WA 98195, USA. E-mail: grunbaum@ocean.washington.edu

animal aggregations: How do they do it? Coordinated motion by locusts and other large animal groups is remarkable, because these groups lack centralized leadership and each individual can interact with only a few nearby neighbors. Group members have no direct means of assessing overall group characteristics, such as size and direction of travel. For these groups to remain intact, behavioral interactions among members must somehow propagate directional information from the large scale—in the case of locusts, millions of individuals distributed across tens of kilometers—down to a neighborhood on the scale of a few centimeters surrounding each individual member.

This information is of no small value. In dense locust populations, the only undepleted resources are ahead of the traveling aggregation. Each member's access to food depends on its ability to at least occasionally anticipate the group's direction of travel and to beat the masses to virgin fodder.

What behavioral mechanisms are involved in this information transfer in locusts and other animal groups? This is the core question addressed in the Buhl *et al.* study. Despite the wide diversity of animal aggregations, there are likely far fewer fundamentally different types of grouping behaviors. By understanding one group, we will probably also understand many others. However, it has proven difficult to identify the precise behaviors used by grouping animals. One obstacle is the difficulty in accurately quantifying movements by entire neighborhoods of animals in the midst of large mobile groups. Another is that most mathematical tools for analyzing biological movement are designed to infer movement characteristics from known interaction rules (*8*). These tools do not work in reverse; they do not extract interaction rules from observed movements.

Buhl *et al.* solved the tracking problem by studying immature, flightless locusts, and they used computerized motion analysis to obtain high-resolution, two-dimensional positions and orientations of all individuals within an annular experimental enclosure. Their study's first key message is that two distinct transitions in group-level directionality occur as locusts become increasingly crowded. At low population density, locusts tend to have random orientations and do not align with one another. Because locusts interact only over relatively short distances, neighbors who are not aligned move quickly

apart and thereafter have little effect on each other. The first transition occurs at intermediate density, when locusts begin to align in neighborhoods to form coherent traveling groups. However, these groups' movement directions are not persistent; they undergo frequent directional changes that are spontaneous and unpredictable. As density increases still further, a second transition occurs in which locust groups that are already aligned acquire the high directional persistence that is characteristic of locust migrations in nature.

Getting a move on. An aligned group of desert locusts, *Schistocerca gregaria*, in Mauritania.

Buhl *et al.* addressed the lack of deductive tools for behavior analysis by showing a detailed correspondence between alignment transitions in locusts and those in an idealized mathematical model of animal grouping. Since the 1920s, the standard hypothesis for organized movements of biological groups has been that group members move toward and align with neighbors within specific ranges of relative positions (*9*, *10*). Neighbors outside these attraction and alignment zones are either too distant to provoke a reaction, or may be so close that they induce an anticrowding avoidance response. Most grouping models also include a stochastic movement component, representing intrinsic behavioral randomness or responses to environmental noise. Behavioral randomness tends to break down ordered arrangements among neighboring individuals. Thus, in these models, the key dynamic process that determines the timing and extent of biologi-

cal grouping is a competition between the tendency of social interactions to induce directional order and the opposing tendency of behavioral randomness to induce disorder.

Buhl *et al.* analyzed a simplified version of this grouping model—the self-propelled particle (SPP) model—that includes alignment among neighbors but omits attraction and repulsion (*11*, *12*). This model predicts that as local population density goes up, social interactions increase in frequency and so too do their order-inducing effects. Behavioral randomness does not increase with density. The result is a shift in the order/disorder balance: In sparse populations, organized groups are unstable and transient. However, when density increases to a critical level, a transition occurs in which coherent aligned groups become stable. As these groups move, they encounter and entrain previously unaligned individuals. These traveling groups convey directional information rapidly over large distances, so that eventually the entire population adopts a uniform and persistent migratory direction. Thus, the second key message of Buhl *et al.* is a demonstration of remarkable agreement between this theory and their observed alignment transitions, which they suggest is strong evidence that locusts use SPP-like grouping mechanisms.

The SPP model is general and not tailored to any particular animal species. A model that is simple, quantitatively accurate, and potentially

broadly applicable opens a number of doors to better theoretical and practical understanding of group dynamics. From an evolutionary perspective, the costs and benefits of behavioral choices in groups change dramatically depending on how other group members respond, and they can be deciphered only through quantitative models of behavioral cause and effect. Furthermore, if the organizational transitions seen in locusts are as fundamental as the SPP model suggests, then their presence is not the result of selective fine tuning; for better or worse, these and perhaps other features may be evolutionarily unavoidable aspects of grouping. In applied terms, intelligent management of natural resources depends on

understanding grouping transitions not only in desert locusts, where we may want to derail collective motion, but also in cases such as overexploited migratory fish stocks, where we need to avoid collapse of reproductive aggregations to prevent catastrophic population declines.

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CHEMISTRY

Toward Efficient Hydrogen Production at Surfaces

Calculations are providing a molecular picture of hydrogen production on catalytic surfaces and within enzymes, knowledge that may guide the design of new, more efficient catalysts for the hydrogen economy.

Jens K. Norskov and Claus H. Christensen

Hydrogen is considered by many to be a promising energy currency, particularly for the transportation sector and for mobile devices (*1*). The combustion of hydrogen yields water as its only waste product, and hydrogen is a perfect fuel for fuel cells. In most hydrogen-producing technologies, a solid surface catalyzes the required chemical reactions. Higher efficiencies require the development of better catalysts. Recent studies have raised hopes that combined computational and experimental surface studies can aid the design of new catalysts.

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To realize a hydrogen-based fuel economy, hydrogen must be produced in an efficient and sustainable manner. Today, most hydrogen is produced from fossil resources by steam reforming, a process in which steam reacts with hydrocarbons in the presence of a metal-based catalyst. Sustainable alternatives include biological or catalytic degradation of biomass and electrochemical or photochemical splitting of water. But irrespective of how the hydrogen is produced, the process is endothermic and requires a considerable amount of energy input.

In most steam-reforming processes, this energy is provided as heat (*2*), whereas water splitting is usually performed electrochemically
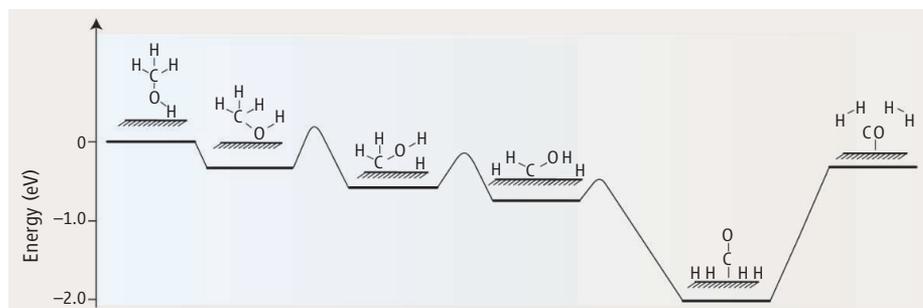
or photochemically (*3*). These processes require bonds to be broken and new bonds to be made, chemical transformations that are activated and typically catalyzed by solid surfaces. Today, the development and optimization of catalytic surfaces is usually based on an intuitive trial-and-error approach. Rational catalyst development strategies would be greatly facilitated by an improved molecular-level knowledge of how chemical reactions proceed on solid surfaces. Recently, new detailed insights have been provided by density functional theory calculations.

Industrial steam reforming of natural gas—that is, $CH_4 + 2H_2O \rightarrow CO_2 + 4H_2$—is conducted with nickel catalysts at temperatures of ~800 °C and provides a convenient and cost-effective method for hydrogen production. Ideally, four hydrogen molecules are formed per methane molecule when the methane reacts with water. Today, compact hydrogen-production facilities with capacities of more than 250,000 m^3 H_2 per hour can be designed (*2*).

Steam reforming of renewable bioresources is also a viable route to large-scale hydrogen production. Glucose can be reformed in water at surprisingly mild conditions, producing more than six hydrogen molecules for each glucose molecule (*4*). Ethanol, available for example through fermentation of biomass, can also be steam-reformed in the presence of oxygen. The required heat is supplied directly by combusting some of the hydrogen produced; such an autothermal process yields five hydrogen molecules for each ethanol molecule (*5*).

The catalytic conversion of alkanes, alcohols, or carbohydrates with water into hydrogen and carbon dioxide are complex multistep chemical reactions. It is not possible to pinpoint a priori why one catalytic surface performs better than another. For even the simplest alcohol—methanol—the number of elementary reactions associated with its decomposition and the subsequent formation of molecular hydrogen is large (*6*). However, calculated potential-energy dia-

J. K. Norskov is in the Department of Physics, Technical University of Denmark, 2800 Lyngby, Denmark. E-mail: norskov@fysik.dtu.dk C. H. Christensen is in the Department of Chemistry, Technical University of Denmark, 2800 Lynby, Denmark. E-mail: chc@kemi.dtu.dk

Understanding catalyst activity. This calculated potential-energy diagram (*6*) shows one way in which methanol decomposes into molecular H_2 and adsorbed CO over a platinum surface. Elucidating this and other competing pathways for decomposition may help to devise new catalysts.

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