

Statistical physics is for the birds

Three-dimensional mapping of starling flocks could shed light not only on the birds' collective behavior but also on a broad range of other aggregate systems.

At dusk each winter evening, millions of starlings fly in from the countryside to their roosting sites in Rome and, before settling into trees for the night, "they spend something like 20 minutes doing these incredible aerial displays. It's a truly amazing sight," says Andrea Cavagna, a statistical physicist at Italy's National Institute for the Physics of Condensed Matter (INFN). "If you watch a flock of starlings under attack by a predator, they split, merge, and do all these incredible maneuvers to confuse the predator. How can they keep cohesion in the face of that strong perturbation—the attack?"

Inspired by the aerial displays, a group of scientists led by theoretical physicists in Rome set up StarFlag, a multidisciplinary, multinational collaboration to study the birds' flocking behavior. The main aim was to determine "the fundamental laws of collective behavior and self-organization of animal aggregations in three dimensions," says Cavagna, the project's deputy coordinator. In addition to the Rome INFN group, which focuses on collecting quantitative data on flocking, the project includes physicists and theoretical biologists who do computer modeling, biologists who study details of starling flight and behavior, and physicists and economists who work on extending the starlings' collective behav-

ior patterns to such systems as cells in wound healing, aggregates of robots, and financial markets.

Three-dimensional data

Many earlier flocking studies were done with fish. "You put them in a tank, and usually you watch only 20 to 40 fish. We wanted to take data in the field, and this is difficult and expensive to do in water, so we thought about birds," says Cavagna. "You have loads of models and theories [on flocking], but no data whatsoever, especially in three dimensions, so everyone could propose a model and be happy, since there was no comparison with experiments." The reason, he adds, "was that having three-dimensional data on large aggregations of moving animals was considered impossible until now." With StarFlag, he says, "we wanted to start from quantitative experimental data. The backbone of the project was to collect three-

dimensional data on large aggregations—thousands, rather than tens, of animals—understand what's going on, and then formulate, or reformulate, models in feedback with the data."

Collecting the data involved setting up cameras each evening on the roof of a building near the Rome railway station. "To do three-dimensional imaging, you have to do stereoscopy. It takes an hour and a half to mount everything, align the cameras, synchronize the electronics," says Cavagna. Then, during the 20-minute aerial display, the team shoots 10 frames per second for a maximum of 8 seconds, until the cameras' memories are full. What they record is a matter of luck, since "once they're set up, we can't move the cameras, so we just stay there, fishing in one place." Flocks can be too big to photograph, or they may not stay in the field of view.

A given flock can have anywhere from 200 to 50 000 starlings, and once



HUGUES CHATÉ AND FRANCK RAYNAUD, CEA-SACLAY



STARFLAG PROJECT, CNR-INFN

Starlings flock every winter evening above the Rome railway station (left; see also cover). The simulation above is based on a three-dimensional model with birds as particles of fixed velocity. The model accounts for alignment and builds in pair-wise isotropic attraction and repulsion. Says Saclay's Hugues Chaté, who made the simulation, "Visually we are doing well. We are now working on how to characterize changing [flock] shapes in three dimensions."

you have the data, says Cavagna, “you have to say who is who in two pictures, and you have more or less lots of black dots. Matching was the bottleneck. It took two years for us to crack this problem using statistical physics methods. It’s an optimization problem.”

Anisotropic interactions

Flock cohesiveness was a mystery, says Cavagna. “It’s clear that the interaction [between birds] decreases with increasing separation, but how do the birds measure distance? We came in as physicists, our experience was with spin glasses, and we used the same tools.” Those tools include techniques from statistical physics, optimization theory, and computer vision. Quantifying the interaction among birds is StarFlag’s most important result so far, Cavagna says.

The Rome team found that a given bird interacts not with all birds within a certain distance, as most models had assumed, but rather with a fixed number of neighboring birds, independent of how far apart they may be. “If flocks always had the same density, there would not be a striking difference between this [behavior] and interacting with all birds within a certain distance,” says Irene Giardina, another statistical physicist in the 10-strong INFN group. “But when a flock is attacked, it undergoes rapid changes in density. You can watch a flock split, but it comes together again. We asked what sort of interaction can guarantee such a robust resilience to perturbation.”

“We looked at our three-dimensional data and considered a given bird, and then we measured the angular positions of its nearest neighbors,” she continues. The distribution of angular positions turns out to be anisotropic, a result that StarFlag scientists presented at a couple of conferences over the summer. “There is much more probability of finding its nearest neighbor on the side, rather than in front or back along the direction of motion,” says Giardina. “We measured this probability also for the second and third neighbors, and so on. And we found that birds interact with six or seven neighbors. After that, the anisotropy decays. That’s the point where the spatial structure becomes isotropic.”

It turns out, Giardina says, that these “topological interactions are much more robust to perturbations” than a model in which a bird interacts with other birds within a fixed distance. The anisotropy, she adds, makes sense biologically: “It’s related to vision, since the physiology of the eye is not isotropic.”

The Rome team is now extending the data analysis to reconstruct trajectories of individual birds. “We don’t have results yet,” says Cavagna. “We have to find algorithms for dynamical matching. But we will be able to ask new questions, such as ‘How long does a bird remain correlated with its neighbors?’ and ‘How does a flock rearrange itself when it turns?’ ”

Model behavior

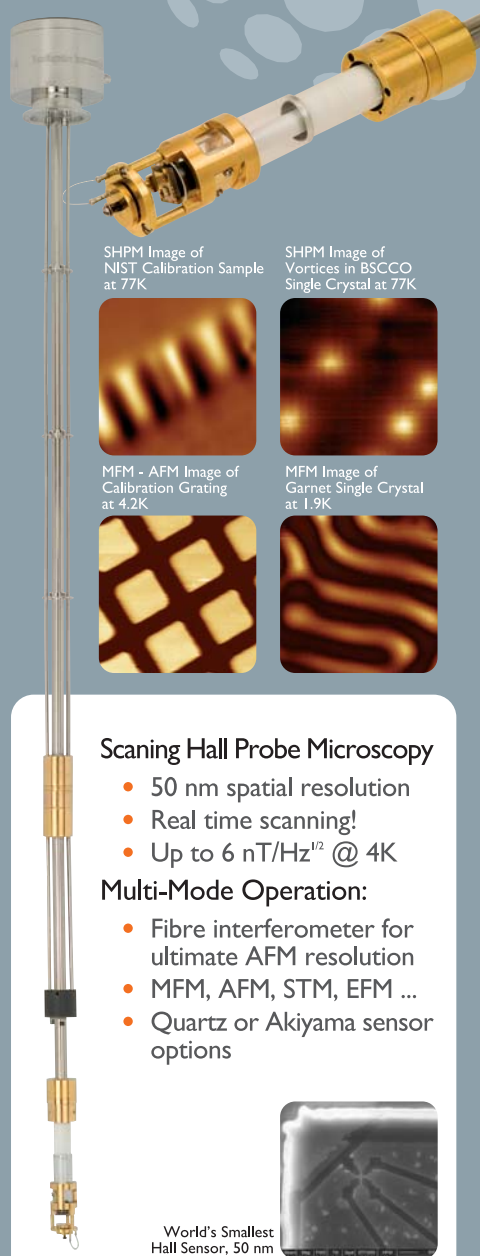
Although computer models of flocking don’t yet explicitly build in the anisotropy, StarFlag’s modelers have refined their simulations since the collaboration began in 2005; the project’s three-year grant from the European Commission runs through this year. “We keep three old rules—hard-core repulsion, longer-range attraction, and we assume that the particles [birds] assume the average direction of their neighbors,” says Tamás Vicsek of Hungary’s Loránd Eötvös University. “But now we feed into the model details of the dynamics, such as that the birds change direction, in order to understand landing and how they self-organize behavior.” In particular, Vicsek and others have extended their models to three dimensions. “We have developed a very nice—fast, beautiful—visualization of flocking data points. The graphics shows birds flapping their wings and contracting when moving away,” says Vicsek.

Hugues Chaté, a physicist at the Atomic Energy Commission in Saclay, France, says that to incorporate anisotropy into the attractive and repulsive potentials of his models, “we need to introduce not just an axis for the flight direction, but another for the wings. Then we can modulate the strength of the interactions.” So far, he adds, the interactions in his models rely on a “nice mix of topological and metric criteria”—a bird interacts with its neighbors, but the strength of each pair interaction is modulated by distance, and the “interactions are strictly local, which makes the emergence of collective motion more spectacular.”

The Rome group’s findings of anisotropic interactions and a fixed number of partners with which birds interact were no surprise to Charlotte Hemelrijk, a theoretical biologist at the Netherlands’ University of Groningen, whose earlier models of fish schools showed a similar anisotropy. Modifying the fish models to account for bird behavior and interactions, she says, “caused a remarkable switch in emergent patterns” and yielded the “variable patterns of flocking observed in aerial displays of starlings. We do not

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Low Temperature Scanning Hall Probe Microscope System



SHPM Image of NIST Calibration Sample at 77K

SHPM Image of Vortices in BSCCO Single Crystal at 77K

MFM - AFM Image of Calibration Grating at 4.2K

MFM Image of Garnet Single Crystal at 1.9K

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need to incorporate these findings [of anisotropic interactions] in our model. They come out automatically due to the coordination among individuals and their movement direction. It is what you expect of animals, due to limitations of perception and cognition." Compared with physicists' flocking models, she adds, biologists "make models that are closer to animals. We try to incorporate flight dynamics—how birds cope with gravity to produce lift and how they turn corners."

"We come from very different viewpoints," says Chaté. As a biologist, Hemelrijk "is worried about the details [of flight]." In contrast, he adds, physicists try to get rid of details. "StarFlag is an opportunity to talk to each other and learn each other's points of view, and to meet somewhere in the middle, or at least get closer to each other." The StarFlag scientists expect their results

on starlings to apply, with tweaking, to other birds, fish, insects, bats—any species that swarms or travels in schools.

Collective glue

And then there is the question of whether starlings might shed light on human behavior. StarFlag's Jean-Philippe Bouchaud, a theoretical physicist who heads research at a hedge fund in Paris, asks, "How do people coordinate and imitate each other to create collective phenomena that are surprising if you think about individuals? People are extremely influenced by their neighbors, by fashions and fads. This might have an impact on markets—possibly events like crashes or bubbles are due to the coordination of people. We are looking for situations where you can measure, or try to measure, the ways people interact and

create a collective effect."

Bouchaud is currently focusing on two examples of human behavior. One involves how others' choices affect what music people download. The other—topical to France's summer elections—is how people are influenced by others when they vote. Along the same lines, a group of economists in Pisa, Italy, is studying the collective behavior of banks as indicated by where they open branches. Starling flocking is more complex, says Bouchaud, "because it's a three-dimensional organization of birds in space. But the idea is to work up from the behavior of individual birds to the behavior of the flock." The connection to studies of people is indirect, he adds. "Behind these projects is the same fascination with collective effects that glues the whole project together. We have a lot of things to share when we meet." **Toni Feder**

Fermilab forms backup plan to avoid science gap

High-intensity beams of rare particles could give Fermilab a vibrant scientific program if delays in the International Linear Collider spell a dry period for the lab.

Anticipating delays with the multi-billion-dollar International Linear Collider, Fermilab wants to get started on R&D for a new \$500 million–\$1 billion accelerator so as to be poised to forge ahead with it if indeed the bigger project is held up.

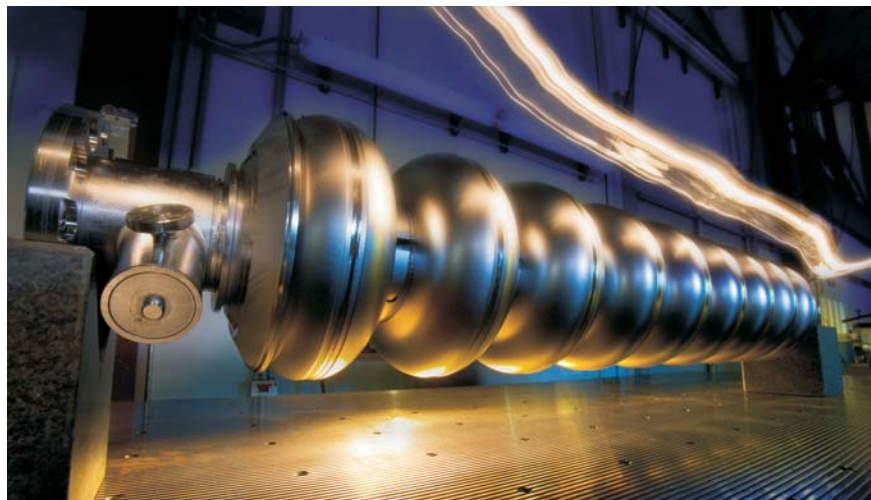
The ILC—an electron-positron col-

lider that would succeed the Large Hadron Collider (LHC), which is set to come on line next year at CERN—is the priority, says Fermilab director Pier Oddone. "Our goal is to host the ILC, and we would like to see that move along and be decided as expeditiously as possible." But, he adds, Fermilab is

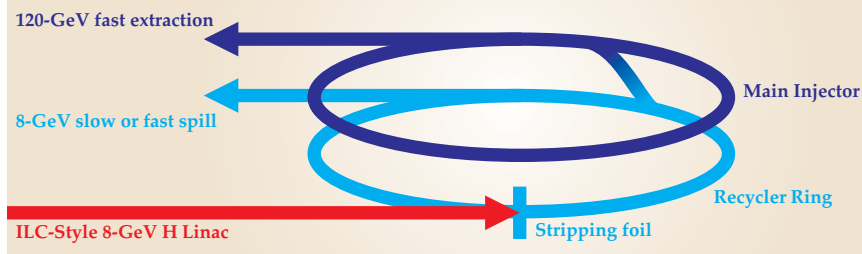
likely to shut down the Tevatron at the end of 2009, so if a decision is not reached to build the ILC soon after that, "the lab is in a peculiar position. And if you look at any historical international agreement, like ITER [the international thermonuclear energy reactor], it took many years to happen. So with a project of that scale, it's prudent to prepare for the fact that we may actually be tied up in negotiations, site selection, and all sorts of things for a number of years."

Intensity frontier

The centerpiece of Fermilab's backup plan is Project X, which would produce a high flux of protons at 8 GeV that could be converted through collisions into high-intensity beams of neutrinos, muons, or kaons. "Project X would pro-



FERMILAB



Project X would pump 8-GeV protons into Fermilab's existing Recycler Ring (light blue in schematic) and Main Injector (dark blue), which would each require some modification. Project X's accelerating portion (red) would include around 200 superconducting RF cavities (top) of the sort the International Linear Collider would use. Protons kicked out by the Main Injector would be high energy and high intensity and would be used for neutrino experiments. High-intensity, lower-energy protons could be extracted from the Recycler Ring to create beams of muons and leptons for other experiments.