telephone). In such cases, they will hardly ever know whether they share $|\psi_0\rangle$ or $|\psi_1\rangle$, and their ability to send quantum states to each other is arbitrarily close to zero (one can make it exactly zero by adding small errors). However, this state is still useful for sending private messages, because Alice and Bob can still just measure as they did before in the $|0\rangle$, $|1\rangle$ basis to obtain a secret key. An eavesdropper may know whether they share $|\psi_0\rangle$ or $|\psi_1\rangle$ but not whether they obtained $|00\rangle$ or $|11\rangle$ after measurement. Thus, channels that produce these flagged states can be used to share private messages, but they cannot be used to send quantum information—they have zero quantum capacity.

Now consider another zero-capacity channel, an erasure channel, that, with probability ½, lets the quantum state through perfectly, and the rest of the time it erases the state; the receiver Bob knows an error occurred because he will measure the error state $|e\rangle$. Such a channel turns out to be useless by itself for sending quantum information, but if Alice first uses the previous zero-capacity private channel and then puts her half of the flag down the erasure channel, then half of the time Bob can combine Alice's part of the flag that he receives from this channel with the other half that he received from the zero-capacity private channel. He can then distinguish the flag. So, half of the time, he will know whether they share $|\psi_0\rangle$ or $|\psi_1\rangle$, and he can perform a correction so that they both share the $|\psi_0\rangle$ state. This means that ¾ of the time, Alice and Bob share $|\psi_0\rangle$ instead of $|\psi_1\rangle$. This is significantly greater than half the time, and enough to create entanglement and get a positive channel capacity.

By using both the zero-capacity private channel and the zero-capacity erasure channel together, Alice and Bob can send any quantum state reliably. In the case above, the inputs that Alice sends through the two channels are not even entangled, but only classically correlated. What's more, this procedure can be easily generalized. All cryptographic protocols must distill the private states of (*3*), and the above protocol can be adapted to work for all of them.

This result raises many questions, not the least of which is what this work may say about the yet unknown formula for quantum capacity. We do not know the optimal procedure for activating a private channel, whether every channel that has zero capacity (but is not classical) can have positive capacity when combined with another zero-capacity channel, or even whether every such zero-capacity channel is also a private channel. Whatever the answers, it is clear that the structure of quantum information theory is much richer than most of us ever anticipated.

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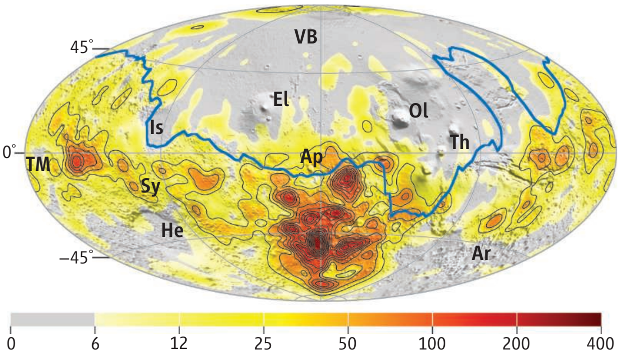
PLANETARY SCIENCE

The Past Martian Dynamo

Numerical dynamo modeling studies may explain the observation that strong magnetic fields are only found in Mars's southern hemisphere.

Benoit Langlais[1] and Hagay Amit[2]

Measurements by Mars Global Surveyor (MGS) have revealed intense magnetic anomalies mostly located south of the crustal dichotomy, the topographic boundary separating the southern cratered highlands and the northern smooth lowlands. Assuming the dynamo of Mars was similar to that of Earth—dipolar, axial, and centered, the magnetic dichotomy implies that the magnetization of the northern hemisphere was erased at some time, and thus that the dynamo stopped operating very early in its history (*1*). On page 1822 of this issue, Stanley *et al.* propose an alternative model in which the dynamo is driven by a hemisphere-scale heat flux pattern at the core-mantle boundary (CMB) (*2*). The proposed thermal constraint is compatible with martian mantle convection models (*3*) and can also explain the crustal dichotomy (*4*). In this new scenario, the much weaker crustal magnetization in the northern hemisphere is not a result of a post-dynamo process such as a giant impact (*5*), but rather, it was never magnetized in the first place.



A magnetic dichotomy. Predicted magnetic field intensity (nT) at 300 km altitude (from (*17*), iso-contours are 25 nT), on top of a shaded relief of the martian surface. Northern hemisphere magnetic field anomalies are of the same order of magnitude as terrestrial magnetic field anomalies at similar altitude, and approximately one-tenth of what is measured in the southern hemisphere. The large impact craters, as well as the large volcanic provinces, show no appreciable magnetic fields at high altitude. Blue line represents the crustal dichotomy. VB, Vastitas Borealis; El, Elysium; Ol, Olympus; Is, Isidis; Th, Tharsis; Ap, Apollinaris Patera; TM, Terra Meridiani; Sy, Syrtis Major; He, Hellas; Ar, Argyre.

Thermal core-mantle coupling can explain some features related to Earth's dynamo. Evidence suggests that the heterogeneous lower mantle affects convection and dynamo action in Earth's outer core. Paleomagnetic field models time-averaged over the past 5 million years show deviations from axial symmetry (*6*). Core flow models time-averaged over the past 150 years show persistent non-axisymmetric features (*7*), and the seismic properties of the upper part of Earth's inner core also exhibit an east-west hemispheric dichotomy (*8*).

Dynamo simulations with heterogeneous heat flux boundary conditions have been used to study the possible impact of the mantle on Earth's dynamo (*9*). The models successfully

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explain some of the observed non-axisymmetric features, such as the locations of the high-latitude intense geomagnetic flux patches in the modern era (*10*). A recent study recovered large parts of the time-averaged patterns of the paleomagnetic field, historical core flow, and inner-core buoyancy flux hemispheric dichotomy (*11*). In these models, core convection is primarily driven from below, whereas the variable boundary heat flux controls its long-term pattern. An upper bound for dynamo action was reported for this type of moderate heat flux anomaly amplitude (*9*).

Stanley *et al.* assume much stronger heat flux heterogeneities at the martian CMB, with convection driven from above maintaining the dynamo. Other aspects that differ from most geodynamo models (*9–11*) include stress-free boundary conditions and hyperdiffusivities. Two additional modeling issues concern the state of the martian core and the heat flux pattern. First, it is thought that the martian core was completely liquid during the first 500 million years (the Noachian era) (*12*). The effect of absence of an inner core therefore has to be evaluated. Second, the proposed dynamo model concentrates its field lines where the heat flux is the largest, i.e., below a cold downwelling mantle, whereas others (*4*) suggest that the thickened crust of the southern hemisphere is related to upwelling. The hemisphere-scale convection pattern in the mantle and its relationship with surface features clearly need to be better understood. Recovery of the single-hemisphere dynamo using different dynamo modeling methods and assumptions may strengthen the robustness of the proposed scenario.

Very little is known about the weak magnetic field signature of the northern lowlands. At 400 km altitude, where MGS spent most of its time, it is indeed very low, with a maximum of 20 nT above Vastitas Borealis. The absence of magnetization in the northern hemisphere (see the figure) may well be due to the single-hemisphere dynamo proposed by Stanley *et al.*, but one can invoke other hypotheses. For example, serpentinization of the southern hemisphere lithosphere, associated with magnetite crystallization and crustal material density decrease (*13*), could also explain the magnetic and topographic patterns on Mars, as could rapidly varying magnetization directions resulting in null to weak fields at spacecraft altitudes.

The proposed model of Stanley *et al.* resolves a number of apparent discrepancies on Mars. The existence of such thermal wind dynamos may open a new avenue for dynamo modeling, for Earth but also for other planets, such as Mercury (*14*). As with Uranus and Neptune, and as opposed to Earth, Jupiter, and Saturn (*15*), the current model shows that the past martian magnetic field was possibly nondipolar and non-axisymmetric. Additional computations and observations are required to validate or dismiss their model. The next breakthrough will come from new observations, first when low-altitude measurements of the magnetic field are made (*16*) and when surface geophysical (seismic, magnetic, and heat flow) measurements are taken as planned by the European Space Agency's forthcoming Exomars rover and associated lander mission. These measurements will give some hints on the current lithosphere thickness, its origin, its relationship with possible hemisphere-scale convection, and the existence of a solid inner core. Combined with thermal evolution models, it will be possible to estimate the thermodynamic conditions on Mars during its early days. These inferences will introduce new geodynamic constraints on models of the past martian dynamo and may shed light on the reasons for its demise. The martian magnetic history is not yet over.

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CANCER

The Metastasis Cascade

Christoph A. Klein

The view of evolution of tumor cells toward metastasis takes a new twist.

The 20th-century philosopher of science, Thomas Kuhn, proposed that when sufficient observational data accumulate that conflict with "received wisdom," the prevailing model gives way to a new paradigm (*1*). With the findings of Podsypanina *et al.* on page 1841 in this issue (*2*), and those of three papers published earlier this year (*3–5*), the field of cancer metastasis seems to be undergoing such a paradigm shift.

For decades, the metastatic dissemination of cancer has been considered the final stage in a deteriorating process. Genetic and (more recently) epigenetic changes have been thought to accumulate in the primary tumor over years before cancer cells are sufficiently mature to spread, having become "fully malignant" (see the figure). Now, Podsypanina *et al.* show that phenotypically normal mouse mammary epithelial cells injected into a recipient animal's bloodstream can survive at ectopic sites such as the lung, until expression of the oncogenes (altered versions of normal genes) they harbor is activated, driving cell proliferation and colonization of a new site. Their findings complement work by Hüsemann *et al.* (*4*) who show that oncogene activation in mouse mammary cells triggers a genetic program, possibly governed by the transcription factor Twist, which enables dissemination of such premalignant cells from mammary tissue to lungs and bone marrow before the appearance of mammary tumors.

How do these results change our understanding of cancer metastasis? The late metastasis model faces the problem that events predisposing a cancer to metastasis are initially unselected, in that they do not provide a growth advantage over neighboring cells (*6*). Thus, the changes promoting metastatic dissemination are mostly associated with tumors large enough to make the change—such as a mutation—a likely event. Proponents of this model hold that by the time of migration, tumor cells harbor compound aberrations that enable their survival by inactivating programmed cell death, which would otherwise be induced by an ectopic environment. Yet Podsypanina *et al.* observed that apparently

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