PLANETARY SCIENCE

Alien Weather at the Poles of Mars

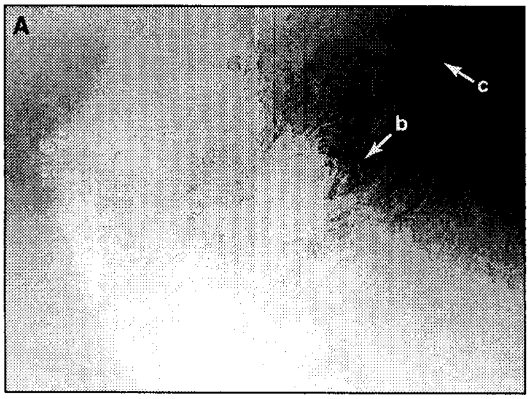
François Forget

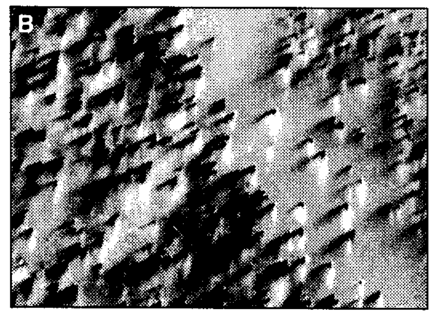
In many respects, the weather on Mars is very similar to the weather on Earth. On both planets, the Hadley circulation (the process that generates the trade winds) is important at low latitudes, whereas "baroclinic" planetary waves (a succession of low- and high-pressure zones) dominate the weather system at mid-latitudes. Of course, Mars is colder and dryer than Earth, and water clouds are less important on Mars than they are on Earth. Conversely, martian mineral dust lifted by the winds is not easily scavenged from the atmosphere and tends to strongly affect the opacity of the thin atmosphere and its thermal structure. Despite these differences, the martian weather usually corresponds to what one would predict for a planet that is a colder, drier desert-like Earth. However, there is one aspect of martian meteorology that has no terrestrial counterpart. This is the direct condensation of the main constituent of the martian atmosphere, carbon dioxide (CO_2), in the polar regions during autumn and winter. In a step toward understanding the martian CO_2 cycle, Sprague *et al.* (*1*) report on page XXX of this issue their analysis of direct measurements of the martian atmosphere taken by the Gamma Ray Spectrometer (GRS) aboard Mars Odyssey. Their analysis reveals unexpected fluctuations in atmospheric composition that create weather with no equivalent on Earth.

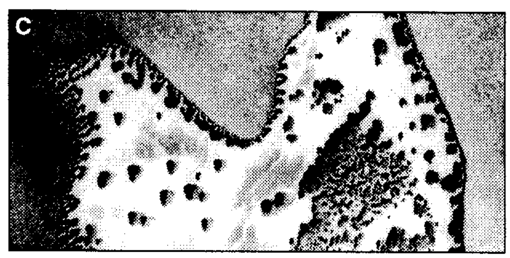
As much as 30% of the martian atmosphere condenses every year to form polar caps in both hemispheres, inducing large surface-pressure variations over the entire planet. At first glance, this phenomenon may seem straightforward, but numerous observations by the NASA Mars Global Surveyor and Mars Odyssey missions, and most recently by the European Space Agency Mars Express spacecraft, suggest that this event is very complex. As is often the case in Mars exploration, the more we observe this phenomenon, the more puzzling it becomes. Many aspects of traditional meteorology and of cloud and snow microphysics must be reinvented to understand the Mars CO_2 cycle. The analysis by Sprague and colleagues reveal a new facet of the CO_2 cycle on Mars: an increase in atmospheric argon over the southern polar regions in autumn followed by its dissipation during winter and spring.

At first glance, the Sprague *et al.* findings are expected. CO_2 condenses on the martian surface to form CO_2 ice, whereas argon and the other noncondensable gases—principally nitrogen (N_2) and oxygen (O_2)—comprising 5% of the martian atmosphere do not. The magnitude of these events, however, is usually underestimated. Indeed, Sprague *et al.* (*1*) now show that the mean argon mixing ratio is enhanced by as much as a factor of 6 during winter and depleted by a factor of 2 to 3 during spring. As a result, the air composition varies strongly with location and season. Indeed, noncondensable gases constitute up to 30% of the bulk southern polar atmosphere during the winter solstice (and probably much more locally) compared to about 5% on average over the planet. Under such conditions, the partial pressure of CO_2 would be lower than expected, the CO_2 frost point temperature would be decreased by several Kelvin, and the surface thermal infrared cooling would be reduced by more than 5%. More importantly, because the mean molecular weight of noncondensable gases is only 32.3 g mol^{-1} (as compared with 44 g mol^{-1} for CO_2), the enrichment of such gases near the surface where most of the CO_2 condenses would induce deep static instability and vertical mixing.

These aspects were considered by Seymour Hess 25 years ago (*2*), but have been neglected in most contemporary models of the martian atmosphere. The new GRS measurements show that the winter martian atmosphere is characterized by a sizable latitudinal gradient of different molecular weight gases that form a deep layer at the edge of the polar vortex. Meteorologists have not previously had to consider such density gradients, although a close analogue would be the gradient of salinity in oceans that oceanographers have had to incorporate into their calculations. In practice, the enrichment of lighter non-condensable gases observed during the winter solstice would have the same affect on the atmospheric circulation as a 13K temperature gradient (which has been used in the traditional thermal wind equation). This gradient would tend to reduce the intensity of the polar







A frozen atmosphere on the ground. The subliming southern seasonal CO_2 polar ice cap in the middle of spring photographed by the Mars Global Surveyor MOC camera. **(A)** Wide angle image (image height: 1500 km). The pole is near the center of the image. The brightest region nearest the pole is the perennial ice cap, which remains covered by CO_2 ice all year long. The other side of the cap on the right is the "cryptic region", which appears to be dark like bare ground probably because the cap consists of transparent slab ice (*8*). During the spring in these regions, the ice tends to sublime from the bottom forming vents that allow pressurized gases to escape. **(B)** This process erodes the surface along "spider-shaped" (*9*) ragged channels that can be seen through the ice, and the ejected material falls downwind to form fans. **(C)** In some other locations, the ejected material forms curious dark spots of puzzling aspect (*7*). **(B)** and **(C)** are MOC narrow angle images (image height: 2.95 km). The global heterogeneity of the subliming cap may be related to its formation during the polar night. The three pictures were obtained a few days apart.

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vortex, and to favor the transport of noncondensable gases outside the polar region.

Another aspect of the martian polar night atmosphere that is far from understood is the formation of CO_2 ice clouds and snowfall. Although it is thought that most of the carbonic ice directly condenses on the surface, a large fraction should also condense in the atmosphere, strongly influencing the radiative properties of the atmosphere and the martian surface (*3*). Most of these clouds form in the polar night, and thus evidence of their existence has remained theoretical (*4*) or indirect (*3*). It is only with the advent of the Mars Global Surveyor laser altimeter MOLA—which acts as a light detection and ranging (LIDAR) instrument—that a variety of cloud shapes varying over space and time have been observed (*5*). There have been several attempts to model the complex behavior of these clouds, which seem to form in topography-induced updrafts, buoyancy waves in the lee of mountains, or even in exotic convection cells (*4*, *6*, *7*). One difficulty is that, because CO_2 is the major constituent of the atmosphere, the microphysics of martian CO_2 ice clouds is unlike that of any clouds on Earth or on other planets of the Solar System.

At the end of the polar night, condensation stops, but the behavior of CO_2 ice does not become simple (*8*). The sublimation of the frozen atmospheric layer is characterized by spectacular albedo changes (*9*) and explosive gas eruptions that erode the surface year after year (*10*) forming curious dark spots of multiple shapes (*8*) (see the figure). In the Southern Hemisphere each year, a large part of the cap (the so-called cryptic regions) remains quite transparent and dark and rapidly sublimates (see the figure). In contrast, other areas at the same longitude become very bright and ultimately outlast the summer to form the perennial CO_2 ice cap at the south pole (*9*). This geographical distribution still has not been explained. Furthermore, the existence of the perennial CO_2 ice cap, a relatively thin (*11*) frozen atmospheric reservoir near the south pole, is puzzling. Any changes in its albedo or the evolution of the planet's orbital parameters (which are highly variable) would make the CO_2 ice cap either disappear or grow much bigger within a few years. Somewhere hidden in the alien meteorology that controls the formation of the martian CO_2 ice cap, there must be some stabilizing feedbacks that remain to be discovered.

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MOLECULAR BIOLOGY

Knives, Accomplices, and RNA

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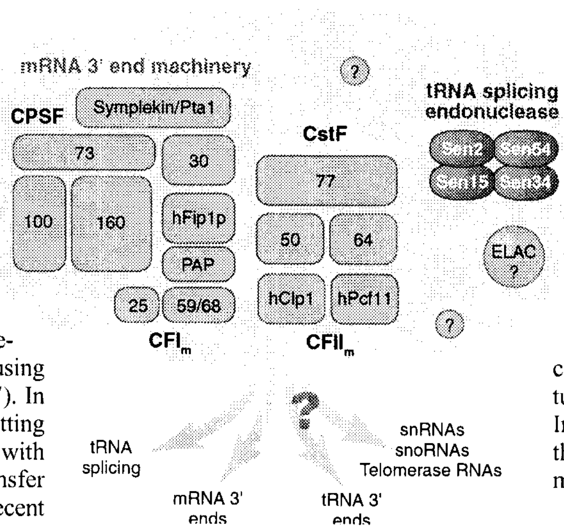
The weapon is missing and the authorities are frustrated. The attacks are simple—a phosphodiester bond is severed cleanly to form the 3′ end of messenger RNA (mRNA), which is then free to receive its tail of polyadenosine [poly(A)]. The attacking gang of proteins is large and well known, but an intensive search has been mounted to identify the culprit that actually cuts the pre-mRNA. A recent study points an accusing finger at one gang member, CPSF73 (*1*). In another clue, proteins involved in cutting pre-mRNAs also physically associate with proteins that cleave pre-tRNAs (transfer RNAs) during splicing (*2*). These recent findings suggest surprising links among proteins that cut different types of RNA.



A Swiss Army endoknife? The tRNA splicing endonuclease (purple) and mRNA 3′-end machinery (green and gray) associate with one another. Proteins in purple associate with those in green (2); proteins in gray have not been tested. The complex may process other types of RNAs, and contain other endoribonucleases (yellow). [mRNA factors adapted from a figure by W. Keller (Biozentrum, Basel)]

Primary RNA transcripts are cleaved by endonucleases to generate the 3′ ends of mRNAs, tRNAs, microRNAs, and certain small nuclear and nucleolar RNAs (snRNAs snoRNAs). The formation of mRNA 3′ ends can be reconstituted in the test tube (*3–6*), and in mammalian cells at least 14 different proteins are required for this process (see the first figure). The factors CPSF and CstF recognize the critical sequences in pre-mRNAs, whereas other factors are required for the cleavage step and for addition of the poly(A) tail. All of these factors, except the poly(A) polymerase (PAP), are complexes containing multiple proteins. Although 900 kD worth of factors have been isolated, it is unclear whether the enzyme that actually cuts pre-mRNA is among them.

A serendipitous clue to the identity of the mRNA endonuclease comes from studies of tRNA processing. Mutations in the *ELAC2* gene appear to cause susceptibility to prostate cancer (*7*). ELAC2 is an endonuclease that cleaves 3′ extensions from pre-tRNAs (*8*) in mammalian cells, like its close relatives in plants and Archaea (*9*). The ELAC proteins are similar in sequence to the 73-kD subunit of CPSF (CPSF73) (*7*, *10*). CPSF73 is a member of a subfamily of metallo-β-lactamase enzymes that cleave nucleic acids using a distinctive structure that coordinates two zinc ions (*11*). Implicit in these reports (*8–11*) is the idea that if ELACs cut pre-tRNAs, then CPSF73 might cut pre-mRNAs.

Ryan *et al.* (*1*) recently showed that the putative active site of CPSF73 is essential for viability of yeast cells. Moreover, mRNA 3′ cleavage in vitro, long thought to be metal independent, is stimulated by zinc, consistent with CPSF73 being the perpetrator (*1*). Yet the case against CPSF73 is open: It is unclear whether mRNA 3′ cleavage is defective in CPSF73 mutants or whether CPSF73 is even a nuclease. Complicating matters further, the *Drosophila* zinc-finger endoribonuclease, Clipper, is related to a different CPSF subunit (*12*, *13*).

The notion that CPSF73 is the enzyme that forms mRNA 3′ ends is seductive, in part because the two steps that form both

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