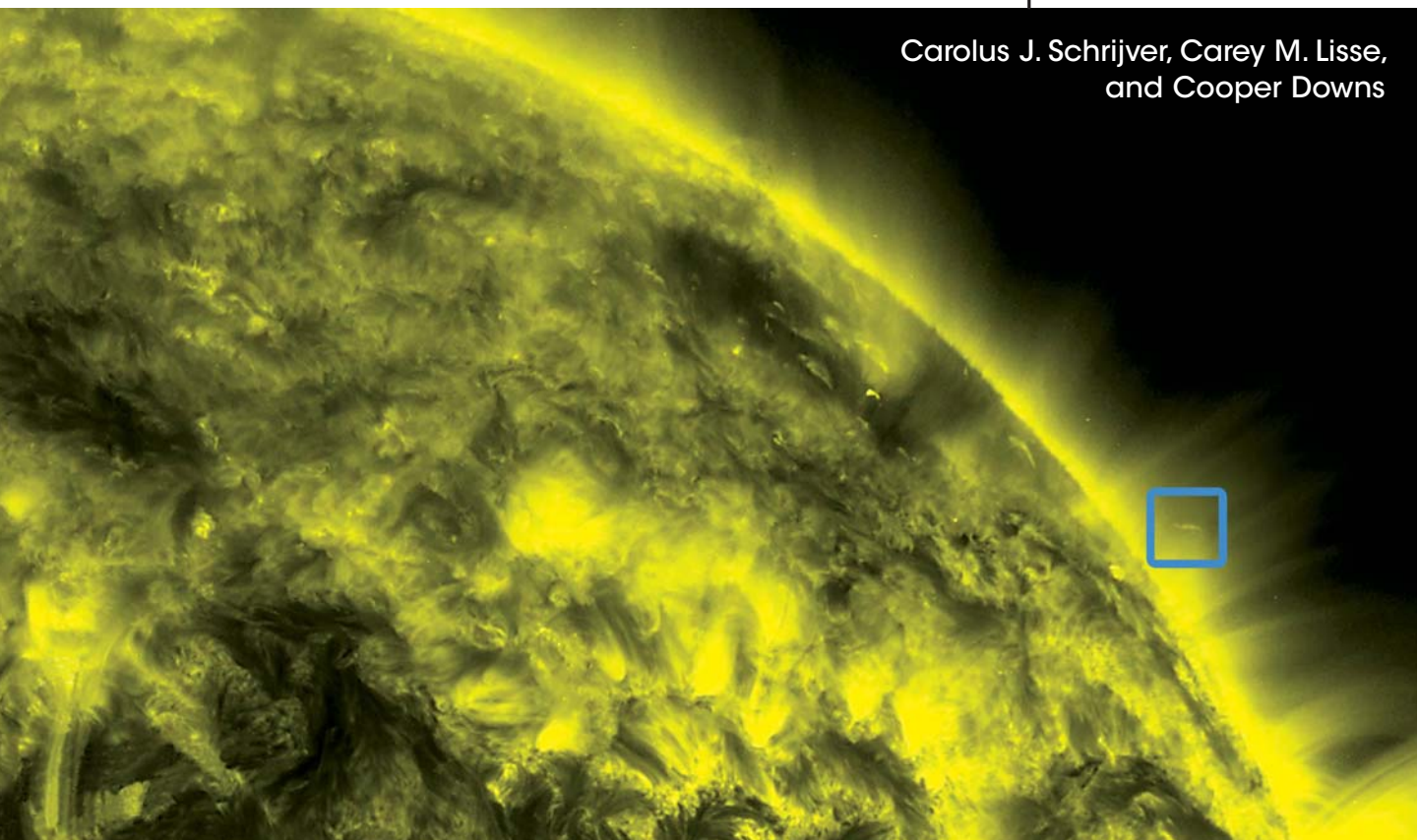


COMETS

as solar probes

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NASASDO AND THE AIA, EVE, AND HMI SCIENCE TEAMS

By rapidly evaporating as they fly through the Sun's hot outer atmosphere, sungrazing comets reveal an otherwise invisible magnetic field that shapes the very beginnings of the solar wind.

Deep inside the Sun, a magnetic field is generated by the effects of rotation-induced Coriolis forces acting on a thermally driven convection that permeates the outermost layer, spanning 30% of the solar radius. That constantly changing field has profound effects: It causes temperatures in the solar atmosphere to rise to millions of degrees to form the x-ray-emitting corona, powers the persistent outflow of charged particles known as the solar wind, and occasionally causes gigantic explosions that drive space weather around all the planets. (See the article by Gordon Holman in *PHYSICS TODAY*, April 2012, page 56.)

The processes that determine which field lines loop back onto the Sun and can hold in the million-degree gases and which ones are forced open into the heliosphere, the region of space through which

the solar wind extends, remain poorly understood because they occur in a domain from which light is hardly emitted and into which spacecraft cannot go. Fortunately, nature recently offered two unexpected probes by which to study that domain: In July 2011, scientists made the first observations of a comet, dubbed C/2011 N3 (sometimes abbreviated N3), moving through the solar corona with its tail lit up in the extreme UV.¹ Only half a year later, the even more spectacular comet C/2011 W3, known as Lovejoy, was traced to within 135 000 km of the

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solar surface, and the comet's tail was seen moving in response to forces exerted by both the Sun's magnetic field and its atmosphere.² Such sungrazing comets leave a trail of gas that, after it heats up and begins to glow, provides a new way to study the local magnetic field and to compare it to state-of-the-art models.

The Sun's complex dynamo

Buoyant bundles of magnetic field float from deep within the solar interior to the surface—or more accurately, the photosphere, the outermost region dense enough to be opaque and thereby resemble a surface. There, they appear in sizes that range from at least a few hundred kilometers in diameter—the smallest scale currently observable—to over 100 000 km across. The largest bundles can form sunspots, in which particularly concentrated fields suppress the near-surface convection and cause the surface to be relatively cool and therefore dark.

The smallest field bundles evolve over tens of minutes in the overturning plasma. The largest ones can resist disintegration for up to several weeks. Eventually, however, all magnetic bundles break up

and disperse, as they are subject to random convection processes, large-scale winds, and collisions in which magnetic field may be removed from the surface. Meanwhile, new bundles breach the surface elsewhere at rates modulated by the Sun's 11-year cycle. The dynamic ensemble of all those field bundles shapes the Sun's large-scale electromagnetic field as it reaches into interplanetary space.

The overturning plasma and small-scale field bundles entrained in it supply nonradiative energy to the solar atmosphere. Dissipation of that energy heats the outer atmosphere to 1–3 MK, some 300 times hotter than the 5780-K solar surface (see the Quick Study by Charles Kankelborg in *PHYSICS TODAY*, April 2012, page 72). This outer atmosphere thereby forms the solar corona, pictured in the center of figure 1, which radiates in the x-ray and EUV parts of the electromagnetic spectrum.

The glow from the almost fully ionized coronal plasma traces the magnetic field from numerous “coronal loops,” as light-emitting ions and the heat-conducting electrons that excite them are locked onto the lines of force. The multi-megakelvin temperature of the plasma produces a substantial pressure high in the multipolar magnetic field. That pressure, somehow aided by the effective pressure of ubiquitous magnetohydrodynamic waves, forces some of the field lines to bulge into the far reaches of the planetary system. The result is an ever-flowing supersonic solar wind of mostly electrons and ionized hydrogen and helium, moving at speeds from 300 to 1000 km/s.

The processes that heat and drive the fluctuating solar wind and its entrained magnetic field are among the primary puzzles of heliophysics. Observational access is difficult. The glow of the innermost, closed-field corona can be measured out to several tenths of a solar radius using space-based x-ray and EUV telescopes. And the solar wind has been measured *in situ* from some 50 solar radii out to distances far beyond Pluto with particle sensors flown on the occasional interplanetary spacecraft. But the region in between, which straddles the top of the corona and the base of the wind, is very difficult to probe.

Space-based coronagraphic telescopes block out the bright solar disk and can routinely view the striations in the solar wind down to about half a solar radius (about 350 000 km) above the solar surface; figure 1 shows such striations in the visible-light portion (red). And occasional solar eclipses provide brief glimpses into the solar atmosphere, even close to the Sun's surface. To map the diversity of coupled physical processes between the corona and the out-flowing wind, scientists are increasingly turning to numerical computation. Current models are subject to a multitude of simplifying assumptions, however, which makes observational validation essential. That validation is what makes observations of two

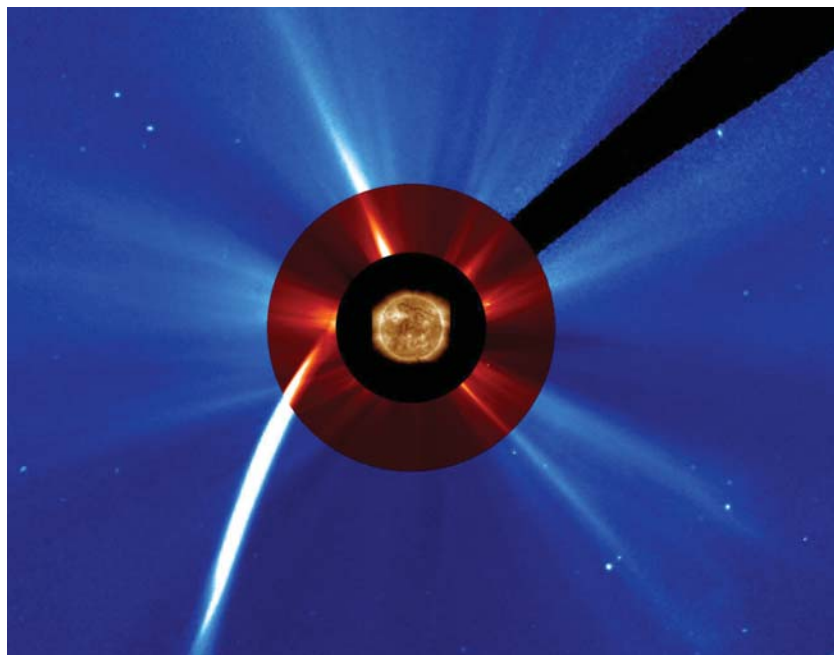


Figure 1. A composite photograph of the Sun and inner heliosphere taken at 01:30 universal time on 16 December 2011. The center exposure, taken by NASA's *Solar Dynamics Observatory* spacecraft, shows a false-color image of extreme UV radiation from gases in the corona at about 1.5 million K. Surrounding that central image are images made using the Large-Angle and Spectrometric Coronagraph (LASCO) aboard the European Space Agency's *SoHO* spacecraft. Two different LASCO telescopes (with image segments shown in red and blue) reveal structures known as streamers, which outline relatively dense coronal regions shaped by the magnetic field, against a backdrop of stars. The arc reaching toward the Sun from the lower left is comet Lovejoy's tail as it approached perihelion. The bright mark near 2 o'clock at the inner edge of the red image shows post-perihelion Lovejoy just beginning to regrow a dust and gas tail after having lost it while closer to the Sun. Within three days from these images, Lovejoy's nucleus completely sublimated and ceased to exist.

comets passing to within 20% of the Sun's radius in 2011 so valuable.

Sungrazing comets

The celestial phenomenon that people see as a comet is created by sunlight scattering off the dust and gas that sublimate from an irregular kilometer-sized chunk of ice-cold primordial solar-system matter. Comets whose orbits bring them relatively close to the Sun are readily visible because large amounts of cometary ices evaporate off their surfaces and release embedded dust as they do. As figure 2 shows, scattered sunlight makes the comet tails stand out against the starry sky. Indeed, the tails stand out even close to the Sun, provided the Sun's bright surface is efficiently blocked out, as it is by coronagraphs flown on the *SoHO* and *STEREO* spacecraft, which routinely observe comets at great distances from the Sun. Over the past decade, coronagraphs have discovered more than 1600 members of a family of comets named after its discoverer, Heinrich Kreutz.

The Kreutz comets, including C/2011 N3 and Lovejoy, have closely aligned common orbits with a propensity for perihelion distances of less than a few solar radii. Thought to be the remnants of a giant parent comet that fragmented upon its near-Sun passage several thousand years ago, the Kreutz family has been the subject of intense study.³ Some of the brightest comets ever seen were large Kreutz sungrazers. But a steady stream of smaller fragments also arrive more or less continuously with estimated radii³ between about 10 m and 1000 m.^{4,5} Before the sightings of C/2011 N3 and Lovejoy, though, none had been observed to fly through the solar corona.

Leaving a trail

Understanding the physical construction of comets—how micron-sized specks of dust and gas molecules accreted into large ice- and rock-rich bodies—is one of the great mysteries of planetary science. Using known physical parameters such as bulk modulus, porosity, surface cohesion, and dielectric constant, most models of the aggregation of gas and dust show that particles should build up to centimeter-sized objects quite easily in the plane of the solar system. But such studies also suggest that larger-sized particles should disintegrate when colliding with each other, which happens at speeds of a few kilometers per second or more. Thus we face what's known as an aggregational barrier to the formation of planetesimals.^{6,7}

Past that barrier, accretion into the known planet-sized objects is relatively straightforward to understand (see the article by Robin Canup in *PHYSICS TODAY*, April 2004, page 56). The size distribution of fragments of sungrazing comets can tell us about the sizes of the bodies that formed the parent comet. Moreover, such sungrazers are probes to a temperature regime, on the order of 500–2000 K, that is not otherwise encountered in the solar system. In that regime, comets emit material through sublimation and thermal desorption. Thus, remote-sensing spectroscopy of sungrazers can yield in-

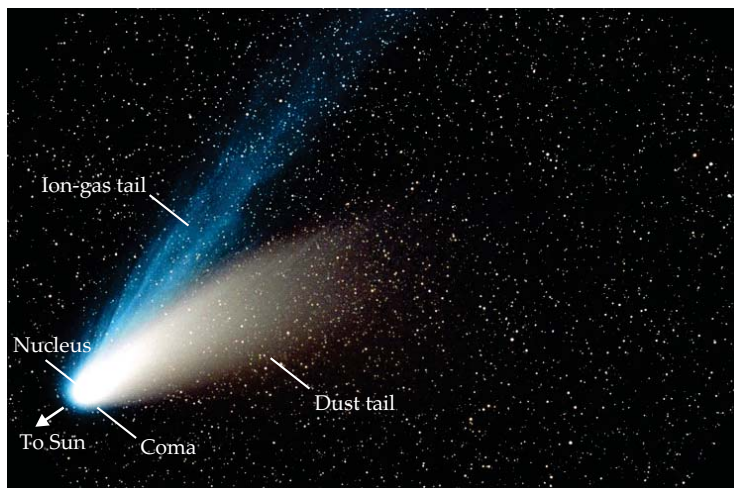


Figure 2. An image of comet Hale-Bopp in March 1997 when the comet was about 1.01 AU from the Sun. The nucleus of Hale-Bopp was unusually large, with a radius of 25–50 km; by comparison, a typical comet nucleus is 1–10 km in radius. The Hale-Bopp nucleus is here surrounded by a 100 000-km haze known as the coma. Two tails stretch away from the haze. The gray dust tail, pushed back from the coma by the pressure of sunlight, stretches over 33 million km. The bluish ion tail is pushed away from the Sun by the solar wind and its embedded magnetic field.

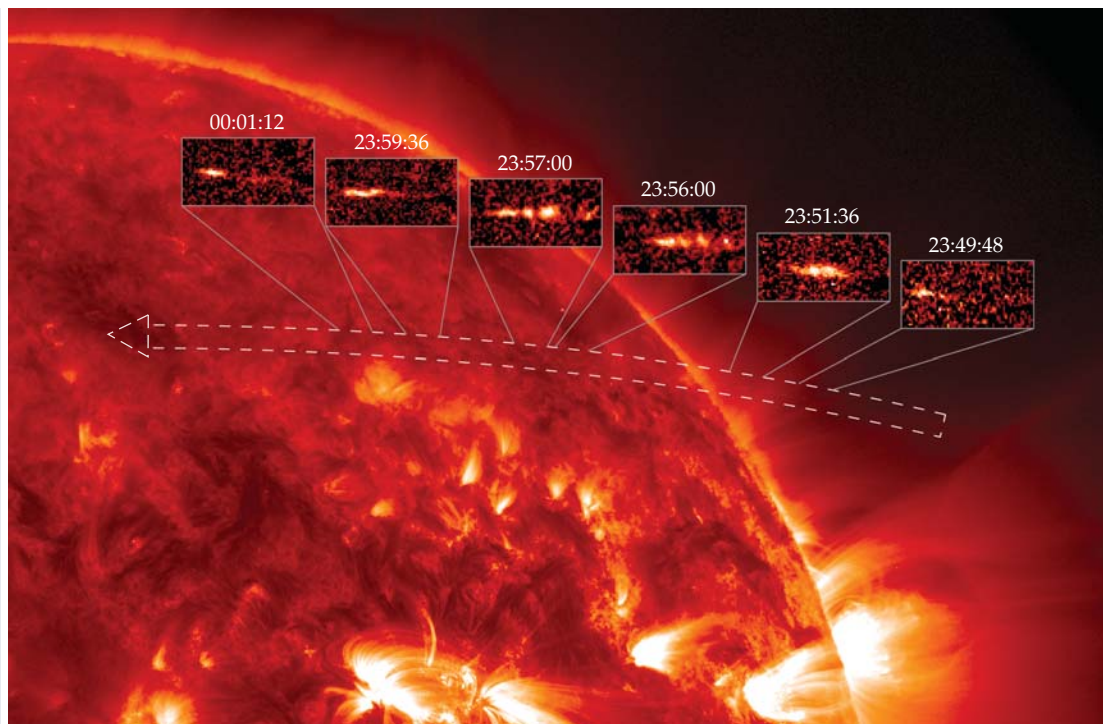
sight about the least volatile components that make up comets and presumably the rest of the bodies in the solar system (see the article by Don Brownlee in *PHYSICS TODAY*, June 2008, page 30).

No one has yet worked out the details of what happens to chunks of matter once they leave a comet nucleus. They're known to actively sublimate and lose mass in sunlight. But as long as the chunks remain large enough to efficiently cool themselves by evaporation, they can maintain their surface near the sublimation temperature of water ice—about 200 K. When that cooling no longer suffices, they rapidly heat up to thousands of degrees and explode into tiny pieces of dust and ice. The pieces quickly evaporate into a gas of molecules that then rapidly dissociate in sunlight and through collisions with the coronal plasma. That fate happened to N3, whose nucleus, coma, debris tail, and path across the face of the Sun are shown in figure 3.

The rate of comet mass loss near the Sun is large by human standards: It's estimated¹ at 1–100 tons/s for N3. Nonetheless, the telescopes used to image N3 and Lovejoy—the Atmospheric Imaging Assembly⁸ aboard NASA's *Solar Dynamics Observatory* (*SDO*) for N3 and the AIA and the SECCHI telescopes aboard NASA's *STEREO* spacecraft for Lovejoy—detected gases escaping from debris fragments no more than about 400 m in diameter against a bright star with a diameter some two million times as large as the fragments.

Detecting that signal against the coronal glow is possible because the solar corona is made up of over 99.9% hydrogen and helium ions by number, but a comet, having lost almost all of those volatile species, consists predominantly of water ice and

Figure 3. Extreme UV images of comet C/2011 N3 as it passed in front of the Sun on 6 July 2011. The images were taken by NASA's *Solar Dynamics Observatory* using its 171 Å channel, which is most sensitive to emission from coronal plasma near 10^6 K. The insets show running-difference images—each subtracted from an exposure in the same region taken several seconds earlier—to isolate the comet's tail from the background solar corona. The appearance of fragments is attributable to variable outgassing rates rather than to substantial separation of nuclear fragments. (Courtesy of Wei Liu, Stanford University.)



rock, with more than 40% oxygen atoms and about 5% iron atoms by number. Consequently, an ablating comet locally enriches the solar coronal plasma with first neutral and then ionized O and Fe atoms. Those ions' subsequent glow from collisions with electrons adds measurably to the characteristic coronal EUV photons to which the state-of-the-art instruments on *SDO* and *STEREO* are tuned.

Falling through the atmosphere

For any cometary nucleus that survives to within 25 000 km of the solar surface, the solar atmosphere would be dense enough—exceeding 10^{11} cm $^{-3}$ —that drag and the stresses of deceleration would be huge.⁹ Those forces can create an exploding airburst followed by a fireball that spreads and rises through the atmosphere, just as comet Shoemaker–Levy 9 did when it fell into Jupiter¹⁰ in 1994 (see *PHYSICS TODAY*, February 1995, page 17). The Sun itself provided a scaled-down view of such impacts on 7 June 2011. On that day, dense clouds of cool gas that were ejected from the solar surface during an unusually large filament eruption fell back onto the Sun, reaching impact velocities up to 450 km/s.¹¹ Within some 10 seconds of their descent from hot corona to solar surface, the falling clouds experienced a billionfold increase in atmospheric density. The resulting explosion was clearly visible in the UV and EUV and produced a spray of matter heated in excess of a million kelvin.

Comets N3 and Lovejoy did not come that close to the solar surface, however. They reached only to about 110 000 km and 135 000 km, respectively. The fate of comets at those distances is dominated by sublimation,⁹ even though they are moving in free fall at nearly the escape velocity of 650 km/s, or 0.002 times the speed of light. The sublimated atoms and

small particles quickly decelerate behind the nucleus into the coronal rest frame in collisions with the atmosphere. They thus lose their kinetic energy and momentum in tens of seconds and thereby warm to EUV-emitting temperatures at densities high enough to be detectable against the background coronal emission.

The free-fall velocity of a sungrazing comet near perihelion lies in the range of typical solar-wind speeds (300–800 km/s) that comets encounter far into the heliosphere. Hence, the relative velocity of the solar plasma for a sungrazing comet near perihelion is comparable to that for a comet much more distant in the heliosphere. What mainly distinguishes comets probing the two environments are the rate of molecular dissociation following sublimation and the rate at which atoms collide with the surrounding medium. The density of the solar wind near Earth's orbit, for example, is 3–10 atoms/cm 3 . Within the corona near the perihelions of N3 and Lovejoy, in contrast, the density is on the order of 10^8 atoms/cm 3 .

In the distant heliosphere, radiation pressure on the gas and dust tail is the dominant force, with some ionization of cometary atoms producing a second, windswept tail, as shown in figure 2. Near the Sun, however, the collisions of the monoatomic gases with the solar atmosphere dominate. The result is that the comet's tail becomes ionized plasma and thus feels the force of the solar magnetic field. Dust and molecular gas survive too briefly to be visible, and the ion tail quickly decelerates into the rest frame of the coronal plasma and its all-permeating magnetic field. For Lovejoy, no dust survived to be blown out into the heliosphere for about 2 days (or 0.17 astronomical unit) on either side of its perihelion passage. Even gas molecules were quickly bro-

ken up: The dissociation of water molecules, for example, would have taken only 3 seconds, followed by ionization of its atoms in less than 0.1 second.¹²

Probing the corona

All known Kreutz comets were discovered as they were falling toward the Sun. But before Lovejoy approached it in late December 2011, no Kreutz comet had been observed to survive close perihelion passage. Even Lovejoy lasted only 2–3 days after passing through the Sun's corona.¹³ But before Lovejoy's 4.5-billion-year history ended, both the descent and ascent phases of its path were visible to spacecraft looking from three very different perspectives.²

The idea of using comets to learn about the Sun and its surroundings is not new. Observations of linear tails that pointed away from the Sun and glowed due to emission from ionized gases led to the first inklings of what since the late 1950s and early 1960 has become known as the solar wind. The dust tails of comets follow parabolic trajectories consistent with a gravitational pull that is counteracted, if not overcome, by outward radiation pressure. But the trajectories of the linear ion-plasma tails depend on the collisional ionization of sublimating gases in the comet's coma and how they are channelled by the magnetic field blown along with the solar wind.¹⁴

Nowadays, the main puzzles about the solar wind concern the largely unobservable region in which it forms. *In situ* data is nonexistent because the deep corona is simply too harsh an environment for spacecraft. Though the environment is also too harsh for sungrazing comets, their much larger initial masses enable them to survive longer. Observations of sungrazers close to perihelion thus enable us to probe the coronal medium along the comets' well-defined trajectories.

The Lorentz force acts on ionized cometary material, and the resulting ion motions reveal the local orientation of the coronal magnetic field even as the comet's ions decelerate and settle into the coronal plasma. The ratio of the energy density of the coronal magnetic field to the kinetic energy density of the plasma in the comet's ion tail is likely to influence the tail evolution. In N3's case it appears that the comet's inertia dominated: As the cometary plasma decelerated during collisions with the corona's atmosphere, the corona's magnetic field became strongly deformed. In Lovejoy's case, in contrast, the solar magnetic field appeared to largely hold its own.

From their observations of comet Lovejoy, the *SDO* and *STEREO* science teams immediately recognized that the dynamical evolution of the tail contained information about the coronal magnetic field. Tail motions observed during ingress and egress from perihelion, as shown in figure 4, corresponded to neither the radial direction nor a direction tangential to the orbit; the radial direction would be expected if the solar wind were fully developed, and a tangential direction would be expected if the coronal medium had no influence on the comet at all. Instead, the *SDO* and *STEREO* imagers revealed wiggles in the tail about the comet's orbital path through the inner corona.

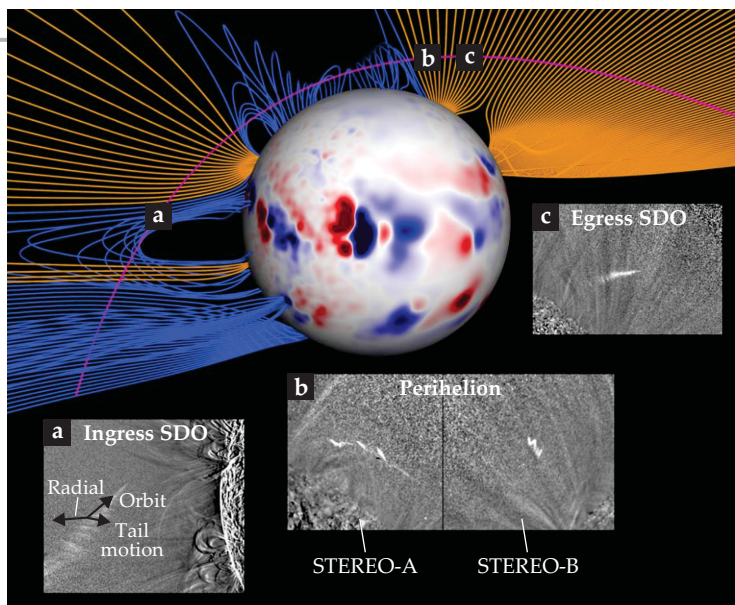


Figure 4. Comet Lovejoy's orbit, shown as the pink arc through the Sun's magnetic field. In the center is the model Sun with magnetic field patches of opposite polarities, red and blue. The insets show snapshots of Lovejoy's tail (white streaks) at different locations, as imaged at 171 Å by the *Solar Dynamics Observatory* (*SDO*) and *STEREO* spacecraft. Scientists have connected the apparent motion of the tail to the simulated magnetic field, shown here as it would appear from above the orbital plane. Orange field lines are open to interplanetary space; blue lines are closed between two points on the solar surface. Ionized comet plasma becomes entrained in the magnetic field and thus provides a natural probe of the corona and a test of magnetic field models. The relative orientation of the field with respect to the comet's path accounts for the nonradial and nonorbital motions that were observed by *SDO* in regions a and c. (For a movie of Lovejoy's approach, see the online version of this article.) The rapidly changing loop orientation of the magnetic field lines near perihelion is consistent with the wiggling motion observed in region b by extreme UV telescopes on the two *STEREO* spacecraft looking from different sides of the Sun.

The varying deflections of Lovejoy's tail indicated a highly inhomogeneous medium. Application of a state-of-the-art computer model of the solar corona² revealed a striking consistency between the observed tail motions and the orientation of the magnetic field. The result provides a unique validation of the model, particularly important given that creating one is daunting.

Creating a global model of the corona starts with the need for a full-sphere map of the field. But currently, only the field in front of the Sun can be reliably measured and only for latitudes up to some 70°. Latitude-dependent solar rotation—with one turn per month, on average—allows researchers to observe the entire low- and mid-latitude belts intermittently from Earth's perspective. Even so, the field evolves significantly in the more than two weeks during which observational access is limited or blocked altogether before the region spins back into view. The field in the polar caps, which generally contribute strongly to the large-scale dipolar field, is always subject to substantial uncertainty.

Because of those observational difficulties, only about one-quarter of the solar surface can be accurately mapped from observations of its magnetic

field. The rest is subject to guesswork or approximations using various assimilative and modeling procedures.

The best-effort global surface map of the magnetic field is used as the foundation for a magnetohydrodynamic (MHD) corona. Disregarding hard-to-model and hard-to-validate large-scale current systems, one such MHD model² varies the parameterizations of atmospheric energy deposition until the forces of the field-plasma interactions balance, selecting the solution in which the computed coronal-brightness patterns best resemble observations. Models like that¹⁵ have been made for some time, and their complexity has increased over the years as computer processing speeds have risen. Lovejoy's passage through the inner corona provides the first detailed test of such models at altitudes where the Sun's corona and nascent solar wind alternate side by side—basically by using the tail motions as wind vanes.

Opportunities

A new comet, dubbed C/2012 S1 or ISON when it was discovered last year, is now approaching the Sun. Its perihelion is anticipated for 28 November 2013 and expected to occur at about 1.2 million kilometers from the solar surface—about 10 times higher in the corona than N3 and Lovejoy. Because density drops rapidly with altitude in the corona, the interactions experienced by a comet at that distance may be dominated by waves and turbulence

rather than by collisions and Lorentz forces. ISON thus promises to probe yet another key region in the nascent solar wind—if indeed it lights up adequately along its orbit to be seen close to the Sun.

Nature provides comets free of charge. The trick is to catch them when approaching the Sun. NASA is now building, at considerable expense in manpower and resources, a spacecraft called *Solar Probe Plus* that will fly late this decade to the very outer reaches of the corona, some 7 million kilometers distant from the Sun's surface. In the meantime, we can take advantage of the free probes to learn as much as possible about the interface between the corona and the enveloping heliosphere at distances far closer than human probes can currently reach.

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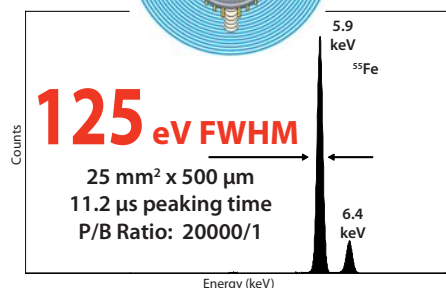
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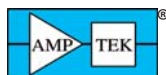
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