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The solar chromosphere and transition region (TR) form an interface between the Sun’s surface and its hot outer atmosphere. There, most of the nonthermal energy that powers the solar atmosphere is transformed into heat, although the detailed mechanism remains elusive. High-resolution (0.33–arc second) observations with NASA’s Interface Region Imaging Spectrograph reveal a chromosphere and TR that are replete with twist or torsional motions on sub–arc second scales, occurring in active regions, quiet Sun regions, and coronal holes alike. We coordinated observations with the Swedish 1-meter Solar Telescope (SST) to quantify these twisting motions and their association with rapid heating to at least TR temperatures. This view of the interface region provides insight into what heats the low solar atmosphere.

Prevalence of small-scale jets from the networks of the solar transition region and chromosphere

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As the interface between the Sun’s photosphere and corona, the chromosphere and transition region play a key role in the formation and acceleration of the solar wind. Observations from the Interface Region Imaging Spectrograph reveal the prevalence of intermittent small-scale jets with speeds of 80 to 250 kilometers per second from the narrow bright network lanes of this interface region. These jets have lifetimes of 20 to 80 seconds and widths of ≤300 kilometers. They originate from small-scale bright regions, often preceded by footpoint brightenings and accompanied by transverse waves with amplitudes of ~20 kilometers per second. Many jets reach temperatures of at least ~105 kelvin and constitute an important element of the transition region structures. They are likely an intermittent but persistent source of mass and energy for the solar wind.

Evidence of nonthermal particles in coronal loops heated impulsively by nanoflares

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The physical processes causing energy exchange between the Sun’s hot corona and its cool lower atmosphere remain poorly understood. The chromosphere and transition region (TR) form an interface region between the surface and the corona that is highly sensitive to the coronal heating mechanism. High-resolution
observations with the Interface Region Imaging Spectrograph reveal rapid variability (~20 to 60 seconds) of intensity and velocity on small spatial scales (≲500 kilometers) at the footpoints of hot and dynamic coronal loops. The observations are consistent with numerical simulations of heating by beams of nonthermal electrons, which are generated in small impulsive (≲30 seconds) heating events called “coronal nanoflares.” The accelerated electrons deposit a sizable fraction of their energy (~1025 erg) in the chromosphere and TR. Our analysis provides tight constraints on the properties of such electron beams and new diagnostics for their presence in the nonflaring corona.

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Hot explosions in the cool atmosphere of the Sun

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The solar atmosphere was traditionally represented with a simple one-dimensional model. Over the past few decades, this paradigm shifted for the chromosphere and corona that constitute the outer atmosphere, which is now considered a dynamic structured envelope. Recent observations by the Interface Region Imaging Spectrograph (IRIS) reveal that it is difficult to determine what is up and down, even in the cool 6000-kelvin photosphere just above the solar surface: This region hosts pockets of hot plasma transiently heated to almost 100,000 kelvin. The energy to heat and accelerate the plasma requires a considerable fraction of the energy from flares, the largest solar disruptions. These IRIS observations not only confirm that the photosphere is more complex than conventionally thought, but also provide insight into the energy conversion in the process of magnetic reconnection.

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The unresolved fine structure resolved: IRIS observations of the solar transition region

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The heating of the outer solar atmospheric layers, i.e., the transition region and corona, to high temperatures is a long-standing problem in solar (and stellar) physics. Solutions have been hampered by an incomplete understanding of the magnetically controlled structure of these regions. The high spatial- and temporal-resolution observations with the Interface Region Imaging Spectrograph (IRIS) at the solar limb reveal a plethora of short, low-lying loops or loop segments at transition-region temperatures that vary rapidly, on the time scale of minutes. We argue that the existence of these loops solves a long-standing observational mystery. At the same time, based on comparison with numerical models, this detection sheds light on a critical piece of the coronal heating puzzle.

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On the prevalence of small-scale twist in the solar chromosphere and transition region

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The solar chromosphere and transition region (TR) form an interface between the Sun’s surface and its hot outer atmosphere. There, most of the nonthermal energy that powers the solar atmosphere is transformed into heat, although the detailed mechanism remains elusive. High-resolution (0.33′′-arc second) observations with NASA’s Interface Region Imaging Spectrograph (IRIS) reveal a chromosphere and TR that are replete with twist or torsional motions on sub-arc second scales, occurring in active regions, quiet Sun regions, and coronal holes alike. We coordinated observations with the Swedish 1-meter Solar Telescope (SST) to quantify these twisting motions and their association with rapid heating to at least TR temperatures. This view of the interface region provides insight into what heats the low solar atmosphere.

The physical mechanism that is predominantly responsible for the heating of the solar outer atmosphere remains unknown. A variety of mechanisms are still under investigation, the most important ones being dissipation of magnetic waves (1–4) or braiding and reconnection of magnetic fields and subsequent energy release (5–7). One mechanism that has recently received attention is the effect of vorticity (8), assumed to be generated by magnetoconvection motions at or below the surface, within the outer atmosphere. Theoretical models predict that vorticity may be a signature of reconnection or magnetic waves or may be associated with strong electrical currents, all of which can lead to substantial heating (8). However, observational support in the solar atmosphere for vortical motions and associated heating has been limited to the chromosphere, that is, lacking a heating component (9, 10); (ii) limited to quiet Sun regions (i.e., away from active regions) (10); or (iii) isolated in incidence and on larger spatial scales (11, 12) than predicted by models (13, 14).

We report observations of twisting or torsional motions that are much more prevalent than previously reported (12), permeate both the chromosphere and the transition region (TR) of the Sun, and sometimes appear to be associated with vigorous heating of chromospheric plasma. We exploited the multithermal chromosphere (<20,000 K) and TR (20,000 to 80,000 K) coverage of the high spatial (0.33 arc sec) and spectral (3 km/s per pixel) resolution near-ultraviolet and far-ultraviolet spectra and slit-jaw images (SJIs) taken with the 20-cm telescope on board the Interface Region Imaging Spectrograph (IRIS) (15), which was launched in June 2013. These data reveal the strong torsional motions (10 to 30 km/s) that imply significant twist in the chromospheric and TR magnetic field.

We analyzed spectroheliograms, that is, raster scans in which the IRIS slit is scanned across the solar surface to build up a three-dimensional view (two spatial and one spectral dimension) in the Mg II h 2803-Å and Si IV 1402-Å spectral lines, which are formed, respectively, in the chromosphere (5000 to 15,000 K) and TR (80,000 K, under ionization equilibrium conditions) (12). From that data, we constructed dopplergrams (12), in which we subtracted the intensities in the blue- and red-shifted wings of a spectral line (at fixed offset velocities from the rest wavelength, e.g., ±30 km/s). The dopplergrams reveal a large number of elongated looplike structures that contain regions of strongly blue- and red-shifted plasma that are in close proximity to one another and that are part of the same dynamic structure (Figs. 1 and 2, figs. S7 and S8, and movies S1 to S20). Most of the plasma imaged in these spectral lines occurs at heights where the magnetic field dominates the plasma dynamics (plasma β ≪ 1) (15–19). Thus, the elongated structures most likely trace the magnetic field and the observed plasma motions are compatible with torsional flows, that is, flows along twisted magnetic field lines; alternative interpretations have been considered but deemed less likely (20). Figure 1 shows the ubiquity of these twisted features in active regions and quiet Sun on the disk and at the limb. The prevalence of these twisted features is actually higher than observed here for several reasons (22). The torsional motions are only visible if the viewing angle is significantly inclined with respect to the magnetic field direction, which is not the case over the whole field of view. In addition, both field-aligned flows and the significant swaying motions in the solar atmosphere (2, 4, 10, 20) render it less likely to see the “ideal” blue-and-red appearance of a twisted feature. Despite these limitations, twist occurs throughout much of the field of view within a variety of structures (Figs. 1 and 2, figs. S7 and S8, and movies S5 to S21). In quiet Sun regions, many of these features appear to be spicules (20), rapidly evolving jets that appear to propel plasma upward and on which torsional motions have been reported before in chromospheric lines (10, 21). However, the IRIS observations now reveal the heating associated with the twisting motions (Fig. 1): The hotter Si IV emission occurs toward the tops of the spicules, both at the limb and more clearly on the disk (where there is less superposition). Moreover, IRIS now reveals prevalent twist also in active region loops that appear to be low-lying and highly dynamic, with both chromospheric and TR plasma involved in the torsional motions (Fig. 1B and movies S5 to S7 and S21). We also see twist in some of the small-scale loops that appear to continuously form in quiet Sun regions (22) and that are visible at the limb.

The amplitude of the torsional motions was estimated from a detailed study of the spectra across the twisted features. Several examples shown in Fig. 2 (and fig. S8) indicate that velocities of order 10 to 30 km/s (over a crossfield distance of 1 arc sec or less) appear to be typical, with one side of the feature more redshifted and the other side more blue-shifted, leading to a tilted appearance in wavelength-space plots. Such tilted features are ubiquitous, especially toward the limb, where the viewing angle combined with the mostly radial magnetic field provide optimal visibility. There are indications that there may even be more locations with significant twist that are not resolved by IRIS. For example, many locations show spectra that do not appear to be tilted but are instead very broad. Such broad profiles could also be caused by bidirectional field-aligned flows or other sources of nonthermal broadening, such as small-scale turbulence. Our observations suggest that at least a significant subset of these broad profiles is likely caused by torsional motions (22).

The temporal and thermal evolution of these twisted features is brought to light more clearly with simultaneous IRIS SJIs (12) and rapid scans in the chromospheric Hα spectral line (Fig. 3) taken with the Crisp Imaging Spectropolariometer Fabry-Pérot interferometer (23) at the SST (24). Chromospheric dopplergrams show that the twisted features are highly dynamic (Fig. 3 and movies S5 to S19) with evidence of rapid propagation of the torsional motions along...
the features, typically 30 to 100 km/s (Fig. 4 and fig. S6). This speed is compatible with the value expected for Alfvén waves in the upper chromosphere and low TR. Typical time scales for the torsional motions are of the order of 1 min (Fig. 2, C and D) with short-lived excursions in the far blue and red wings of the Mg II h 2803-Å line predominant in regions where the line of sight is more perpendicular to the magnetic field.

**Fig. 1. Prevalence of twist in quiet Sun and active regions.** Doppler-grams (A, C, and E) of the chromospheric (~10,000 K) Mg II h 2803-Å line (at 30 km/s from line center) show a multitude of elongated features in which strongly red- and blue-shifted features are parallel and adjacent to each other. These features illustrate that twist is predominant: at the solar limb associated in so-called spicules [(A) and (E)] but also in active regions [(C) and around −250°,−475° in (A)], both regions where the line of sight is likely more perpendicular to the local magnetic field. Twist is often associated with significant brightening in the transition region (80,000 K), as illustrated with the Si IV 1403-Å integrated brightness maps (B, D, and F). When looking straight down plage regions, the line of sight is aligned with the magnetic field, severely reducing or eliminating the visibility of twist. This is why the plage regions have been removed from the active-region dopplergram. See fig. S7 for a larger field of view.
The torsional time scales stand in sharp contrast to the longer time scales (several minutes) and smaller line-of-sight velocities in plage regions (Fig. 2B), where the line of sight is more aligned with the magnetic field and the line profiles are dominated by magnetoacoustic shocks (25).

SJIs taken with IRIS (Fig. 3 and movies S8 to S10) also show how the propagating torsional motions are often associated with bright, highly dynamic linear features (C II 1335 Å and Si IV 1402 Å); this emission indicates heating to at least TR temperatures (20,000 to 80,000 K). In quiet Sun regions, these SJIs appear to be the TR counterparts of so-called rapid-blue-shifted and rapid-red-shifted events in the chromosphere, the disk counterparts of spicules (26). Many of the TR features IRIS observes in quiet Sun regions are associated with twisted features, indicating that the heating we observed is substantial. Some of these events are also visible in coronal passbands (movie S7), although it is not yet clear how much plasma is heated to coronal temperatures in association with these heating events (27).

Our observations of twist that permeates the chromosphere and the TR of the Sun expand on a picture that has recently emerged that draws together disparate observations of twist in the...
solar atmosphere: in macropulsations (27, 28), explosive events (28), spicules (10, 26), and so-called swirls (11, 12). The powerful combination of SST and IRIS observations indicate that, as higher spatial resolutions become available, the apparent prevalence of twist increases. In addition, the unique TR coverage of IRIS shows that the presence of twist is not limited to the chromosphere, but extends into higher temperature regimes and indicates that substantial heating often occurs in twisted features. The occurrence of this twist and the associated heating likely has several causes. It seems possible that the strong photospheric vortical flows that have been observed (29) and that occur in advanced numerical models (8) play an important role. In such models, the vortical flows are often associated with strong currents, and it thus seems plausible that significant heating could result. Some of the observed twist, for example, in the small-scale loops observed with IRIS (22), likely originates from twist in flux tubes that emerge into the atmosphere. Although more advanced modeling and further coronal observations are required, the observed heating is also compatible with recent numerical models that predict significant chromospheric and coronal heating from dissipation of torsional Alfvén waves generated by very small-scale Photospheric vortices (13, 14). The prevalent twist and associated heating are also compatible with dissipation of torsional modes that arise from resonant absorption of waves on flux-tube-like features in the atmosphere (30). Last, torsional motions and heating could also be expected if they result from the reconnection of field lines, for example, as a result of flux emergence (16). Thus, detailed studies of the origin of twist and extent of the heating will open a new window on several proposed heating mechanisms for the lower solar atmosphere. Such studies should also help elucidate the impact of the ubiquitous propagation of small-scale twist on the helicity budget of the solar atmosphere, which may play a role in solar eruptions.

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SUPPLEMENTARY MATERIALS

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Materials and Methods
Supplemental Text
Figs. S1 to S8
References (31–45)
Movies S1 to S22
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