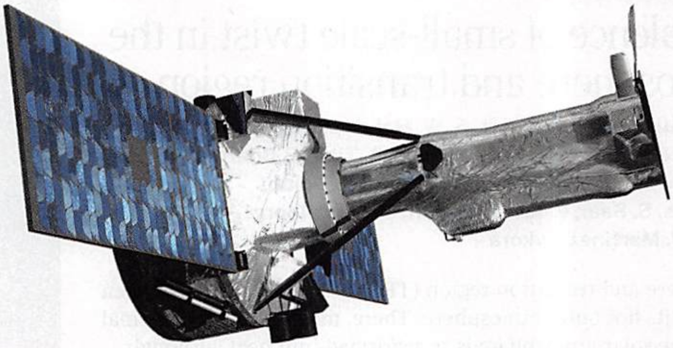

PROBING THE solar interface region

By **Bart De Pontieu,[1] Alan Title,[1] and Mats Carlsson[2]**

The Sun has been the subject of human curiosity since the dawn of time. It provides the energy that makes Earth habitable and is also the closest star to Earth. The Sun thus acts as a laboratory that provides detailed views of physical processes that occur in other, much more distant, astrophysical objects. Much progress has been made in understanding how nuclear fusion powers the Sun's 15-million-degree core and the mechanisms that transport this energy to the visible surface, where most of the light that reaches Earth is released. However, major unresolved questions linger about how the heliosphere, the Sun's outer atmosphere in which we live, is shaped and powered. We do not understand the counter-intuitive rise of temperature from the 6000-K surface to millions of degrees in the Sun's outer atmosphere or corona. Equally puzzling is the solar wind, a high-speed continuous stream of particles that permeates space around Earth. These are not academic problems: Violent explosions such as flares and coronal mass ejections cause bouts of bad space weather that threaten power grids, satellites, and astronauts. These eruptions originate in and travel through this poorly understood solar atmosphere and wind. An important step in our quest to better understand such violent events is then to explore what drives the quiescent state of the solar atmosphere.

In June 2013, NASA launched the Interface Region Imaging Spectrograph (IRIS), an Earth-orbiting small explorer satellite with a 20-cm telescope onboard. IRIS uses gratings to split the Sun's near- and far-ultraviolet light into its constituent wavelengths, in order to remotely probe the physical conditions in the interface region that consists of the chromosphere and transition region. Recent research suggested that it is here, at the interface between surface and corona, that answers to some of the more vexing unresolved questions in solar physics might be found. In this special section of *Science*, five Reports exploit the high-resolution images and spectra obtained with IRIS to present major advances toward a comprehensive understanding of how the solar atmosphere is energized (sciencemag.org/special/iris).

Testa *et al.* find compelling evidence for the presence of high-energy particles generated during coronal nanoflares, small-scale heating events long hypothesized to drive coronal heating through the release of energy when magnetic field lines reconnect. These results provide constraints for models of the poorly understood mechanism that accelerates these electrons to such high energies and that probably acts under many other astrophysical conditions.

Hansteen *et al.* reveal the presence of small-scale magnetic loops in high-resolution images of IRIS and advanced three-dimensional numerical models, resolving a long-standing debate about the nature of the transition region emission. These results vindicate the view that much of this emission does not originate in the "classical" transition region between the surface and the hot loops. Rather, the emission occurs in "unresolved fine structure" that has now been spatially resolved, thereby removing a major impediment to the modeling of coronal loops.

Peter *et al.* exploit the power of high-resolution spectroscopy to reveal a solar atmosphere turned upside down: Hot plasma at 100,000 K is found closer to the solar surface than previously imagined, sandwiched by cool plasma both below and above. The hot plasma is heated by "bombs" in which the reconnection of magnetic fields leads to rapid heating. These unexpected results will likely lead to a reassessment of other phenomena in the low solar atmosphere, such as the mysterious Ellerman bombs discovered almost a century ago.

De Pontieu *et al.* describe a chromosphere that is replete with twisting motions on very small scales that are associated with the heating of plasma to transition region temperatures. They are the signature of propagating Alfven wave pulses and provide support for recently developed models of atmospheric heating and dynamics and insight into the transport of helicity in the solar atmosphere.

Tian *et al.* find evidence of high-speed jets at the root of the solar wind, fountains of plasma that appear to undergo rapid heating from chromospheric to transition region temperatures. These observations provide support for recent suggestions that the solar wind does not necessarily originate only from gentle evaporation in funnels rooted in strong field regions.

Together, these results provide critical pieces in the still-unsolved puzzle of fully understanding of how the Sun shapes and affects the heliosphere. With solar activity at high levels, more advances from the imaging spectrograph onboard IRIS can be expected, especially with respect to flares and coronal mass ejections.

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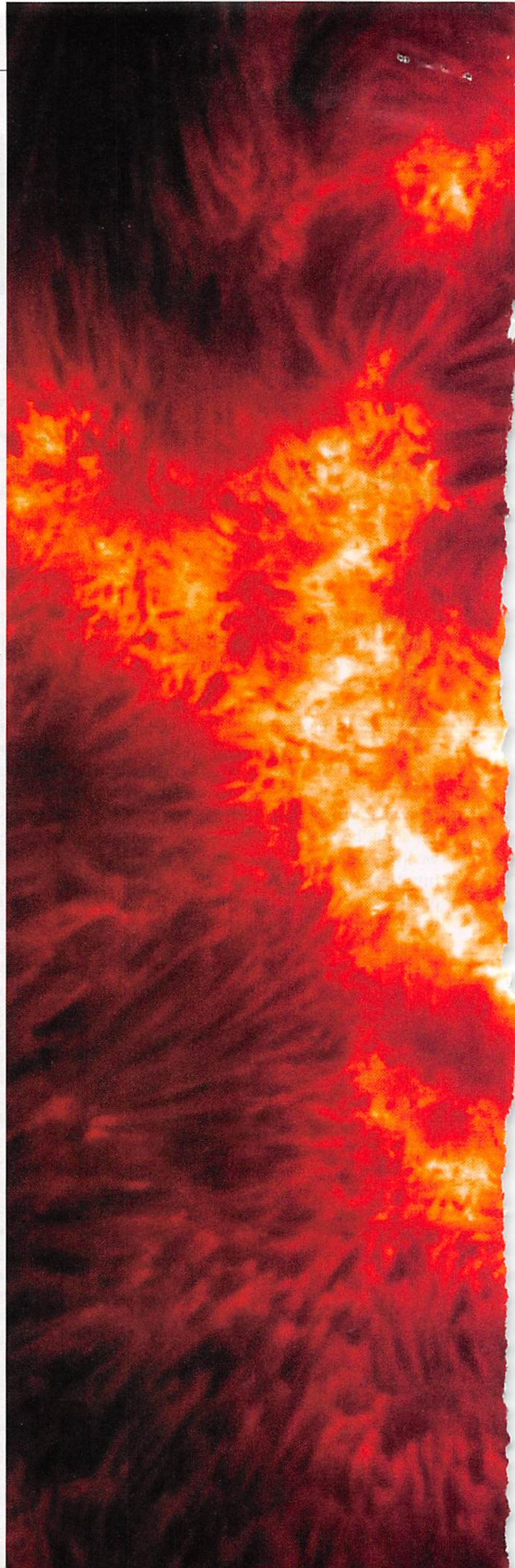

On the prevalence of small-scale twist in the solar chromosphere and transition region

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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 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.

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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 $\sim 10^5$ 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.

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Evidence of nonthermal particles in coronal loops heated impulsively by nanoflares

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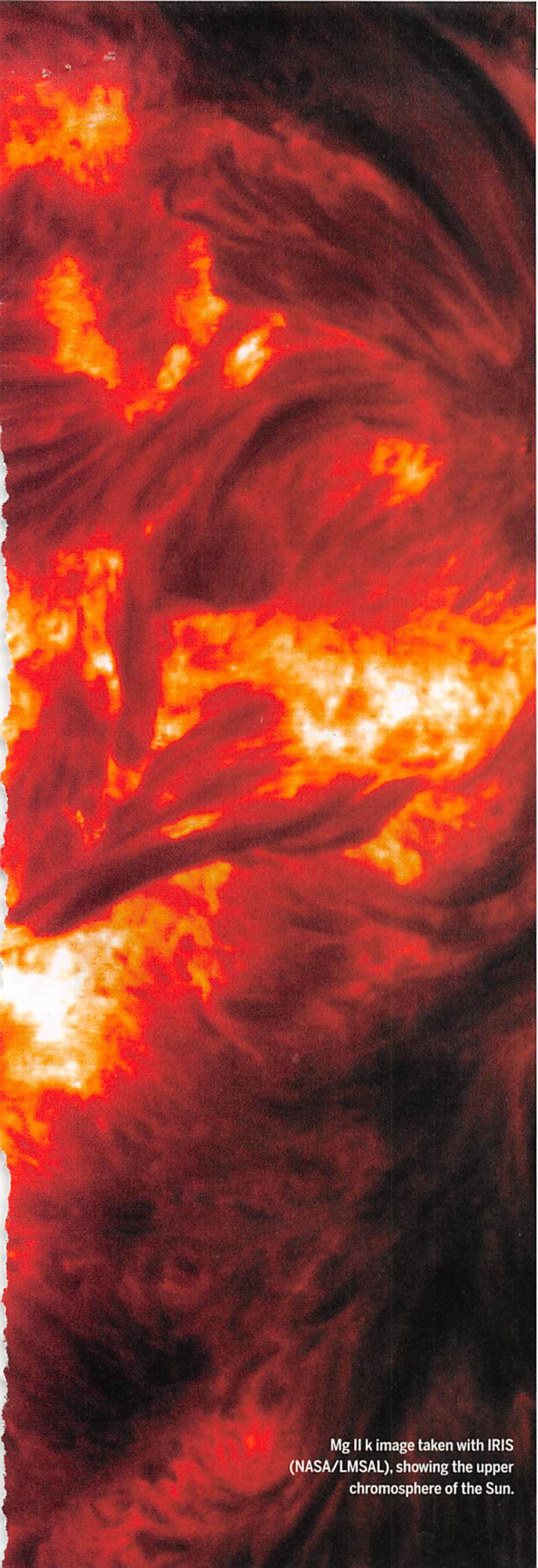
The physical processes causing energy exchange between the Sun's hot corona and its cool lower atmosphere remain poorly understood. The chromosphere and transition region (TR) form an interface region between the surface and the corona that is highly sensitive to the coronal heating mechanism. High-resolution



Mg II k image taken with IRIS (NASA/LMSAL), showing the upper chromosphere of the Sun.

PHOTO: TIAGO PEREIRA, UNIVERSITY OF OSLO, NORWAY

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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RESEARCH ARTICLE

SKILL DEVELOPMENT

Motor skill learning requires active central myelination

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Myelin-forming oligodendrocytes (OLs) are formed continuously in the healthy adult brain. In this work, we study the function of these late-forming cells and the myelin they produce. Learning a new motor skill (such as juggling) alters the structure of the brain's white matter, which contains many OLs, suggesting that late-born OLs might contribute to motor learning. Consistent with this idea, we show that production of newly formed OLs is briefly accelerated in mice that learn a new skill (running on a "complex wheel" with irregularly spaced rungs). By genetically manipulating the transcription factor myelin regulatory factor in OL precursors, we blocked production of new OLs during adulthood without affecting preexisting OLs or myelin. This prevented the mice from mastering the complex wheel. Thus, generation of new OLs and myelin is important for learning motor skills.

Myelin is the spirally wrapped cell membrane that surrounds and insulates axons in the central and peripheral nervous systems (CNS and PNS, respectively). Myelin greatly increases the speed of electrical communication among neurons and, hence, the brain's computational power. CNS myelin is synthesized by oligodendrocytes (OLs), the majority of which develop in the first 6 postnatal weeks in rodents, from proliferating OL precursors [(OPs), also known as NG2 glia] (*1*, *2*). However, many OPs persist in the adult mouse CNS (~5% of all neural cells) and continue to divide and differentiate into myelinating OLs throughout life (*1*–*3*). For example, nearly 30% of OLs in the 8-month-old corpus callosum are formed after 8 weeks of age (*2*). What is the function of adult-born OLs and myelin? Magnetic resonance imaging (MRI) has detected changes in the structure of white matter in people trained in complex sensorimotor tasks such as playing the piano, juggling, or abacus use (*4*–*6*). Analogous MRI changes are observed in rats during motor training (*7*). The histological basis of the MRI change is not known, but one possibility is that newly generated myelin is laid down preferentially in circuits that are engaged during motor learning. Here we show that active myelination during adulthood is required for motor skill learning and that motor learning increases OL production.

Preventing adult myelination by conditional deletion of myelin regulatory factor

Myelin regulatory factor (MyRF) is a transcription factor required in OLs to initiate and maintain their myelination program (*8*–*10*). It is not expressed in OPs, in other CNS cells, or in Schwann cells, which myelinate PNS axons. We have a mouse line that carries a "floxed" allele of *Myrf* (*10*). By breeding (see supplementary materials and methods), we obtained $Myrf^{(+/flox)}$ and $Myrf^{(flox/flox)}$ littermates on a *Pdgfra-CreER*^{T2}*: Rosa-YFP* background (*2*, *11*); we refer to these as $P\text{-}Myrf^{(+/flox)}$ and $P\text{-}Myrf^{(flox/flox)}$, respectively. Administering tamoxifen induces Cre-mediated recombination, inactivating one or both alleles of *Myrf* in *Pdgfra*-expressing OPs while simultaneously labeling the OPs with yellow fluorescent protein (YFP) (see supplementary materials and methods). We refer to the tamoxifen-treated mice as $P\text{-}Myrf^{(+/-)}$ and $P\text{-}Myrf^{(-/-)}$. Recombination at the *Myrf* locus was confirmed by reverse transcription polymerase chain reaction (fig. S1).

We inactivated *Myrf* in OPs by tamoxifen administration on postnatal day 60 (P60) or P90. Subsequently, we identified YFP$^+$ OPs and newly differentiated YFP$^+$ OLs by triple-immunolabeling with anti-YFP, anti-Pdgfra (for OPs), and the CC1 monoclonal antibody (for OLs). In $P\text{-}Myrf^{(+/-)}$ mice, YFP$^+$,CC1$^+$,Pdgfra$^-$ OLs accumulated in the anterior corpus callosum (beneath the motor cortex) after the administration of tamoxifen (post-tamoxifen) (arrows in Fig. 1A). In $P\text{-}Myrf^{(-/-)}$ mice, production of YFP$^+$,CC1$^+$ OLs was decreased to ~10% of control (Fig. 1, A and B); at 1 month post-tamoxifen, we counted 301 ± 59 YFP$^+$,CC1$^+$ cells/mm^2 in 20-μm sections of $P\text{-}Myrf^{(+/-)}$ corpus

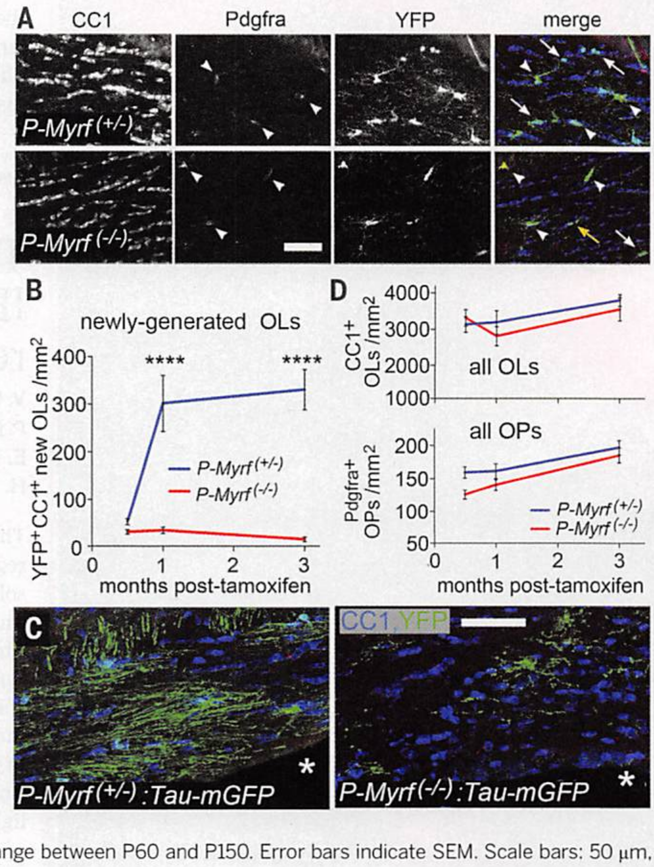

Fig. 1. Deleting *Myrf* in OPs prevents new myelination. (**A**) Many YFP$^+$ (newly formed) cells accumulated 1 month after tamoxifen treatment in the $P\text{-}Myrf^{(+/-)}$ corpus callosum, including Pdgfra$^+$,CC1$^-$ OPs (arrowheads) and CC1$^+$, Pdgfra$^-$ OLs (arrows). In contrast, the $P\text{-}Myrf^{(-/-)}$ corpus callosum contained few YFP$^+$ cells, mainly Pdgfra$^+$ OPs. Some YFP$^+$,CC1$^+$ cells appeared fragmented, presumably because they are apoptotic (yellow arrow). (**B**) Numbers of YFP$^+$,CC1$^+$ OLs in the $P\text{-}Myrf^{(-/-)}$ versus $P\text{-}Myrf^{(+/-)}$ corpus callosum (****$P <$ 0.0001). Error bars indicate SEM. (**C**) Very few GFP$^+$ (newly formed) myelin sheaths are present in the $P\text{-}Myrf^{(-/-)}$*:Tau-mGFP* corpus callosum 1 month post-tamoxifen relative to $P\text{-}Myrf^{(+/-)}$ siblings. Asterisk indicates third ventricle. (**D**) The number densities of Pdgfra$^+$ OPs or CC1$^+$,YFP$^-$ (preexisting) OLs did not change between P60 and P150. Error bars indicate SEM. Scale bars: 50 μm, (A) and (C).

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