The Astrophysical Journal Letters, 755:L11 (5pp), 2012 August 10 doi:10.1088/2041-8205/755/1/L11

# EVIDENCE FOR SHEET-LIKE ELEMENTARY STRUCTURES IN THE SUN'S ATMOSPHERE?

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*Received 2012 March 8; accepted 2012 May 31; published 2012 July 25*

## ABSTRACT

Narrow, thread-like structures in the Sun's chromosphere are currently understood to be plasma guided along narrow tubes of magnetic flux. We report on 1 s cadence imaging spectroscopic measurements of the H$\alpha$ line with the IBIS Fabry–Pérot instrument at the Dunn Solar Telescope, obtained +0.11 nm from line center. Rapid changes grossly exceeding the Alfvén speed are commonly seen along the full extent of many chromospheric threads. We argue that only an optical superposition effect can reasonably explain the data, analogous to striations of curtains blowing in the wind. Other explanations appear to require significant contrivances to avoid contradicting various aspects of the data. We infer that the absorbing plasma exists in two-dimensional sheet-like structures within the three-dimensional magnetofluid, related perhaps to magnetic tangential discontinuities. This interpretation demands a re-evaluation of basic assumptions about low-$\beta$ solar plasmas, as advocated by Parker, with broader implications in astrophysics and plasma physics. Diverse, high-cadence observations are needed to further define the relationship between magnetic field and thermal fine structure.

*Key words:* Sun: atmosphere – Sun: chromosphere – Sun: corona – Sun: surface magnetism

*Online-only material:* animations

## 1. INTRODUCTION

Secchi (1877) documented a solar phenomenon later called "spicules" by Roberts (1945). Spicules appear as thin jet-like structures, several seconds of arc long ($1'' \equiv 725$ km), seen in light of H$\alpha$ at 656.3 nm above the visible solar limb. Hale (1908) later obtained photographic H$\alpha$ spectroheliograms of the solar disk that showed "...a decided definiteness of structure indicated by radial or curving lines, or as some such distribution [...] as iron filings present in a magnetic field." Whether observed at the limb on the disk, both kinds of chromospheric fine structure (henceforth CFS) differ morphologically from the photosphere beneath. In the photosphere, the dominant motions are those of turbulent convection, the magnetic field there conforming to the strong turbulent stresses imposed by convection. But in the overlying chromosphere, the more tenuous plasma appears to be organized into the straw-like CFS by the magnetic fields threading upward. Reviews of CFS observations can be found in Judge (2006) and Rutten (2011).

CFS is generally understood in terms of what it *appears* to be: straw-like jets or tubes of plasma, flowing along particular tubes within volume-filling magnetic fields in the chromosphere, sometimes (as spicules) extending into the corona. This picture follows from two observations. First, the electrical conductivity of chromospheric plasma is high enough so that the magnetic flux threading an elementary volume of plasma remains constant in time ("Alfvén's theorem"). Second, the plasma appears to be in a low-$\beta$ state ($\beta$ = plasma/magnetic pressure) in CFSs, otherwise the plasma's morphology would not appear to be so well ordered. In this (usual) interpretation, those CFS manifested as spicules are important as conduits for mass and energy flow into the corona (e.g., Beckers 1972; Athay & Holzer 1982; Athay 1986; De Pontieu et al. 2009).

But another interpretation was recently advanced (Judge et al. 2011), based on Parker's work on a class of "weak" solutions to magnetohydrodynamic (MHD) equations called tangential discontinuities (TDs). Parker has argued that the Sun's low-$\beta$ atmosphere must spontaneously produce TDs as current sheets (Parker 1972, 1988, 1994). Noting also that sheet-like rivers of magnetic flux appear at least as prevalent as tube-like structures in photospheric magnetic fields seen at the highest resolution, Judge et al. (2011) argued that some CFSs might be projections of the upward extensions of such sheet structures (see their Figure 3 for a sketch). Here we present observational evidence for sheet-like structures seen at uniquely high spatial and temporal resolutions with the IBIS imaging spectrometer instrument, directly within the solar chromosphere.

## 2. OBSERVATIONS AND ANALYSIS

We analyze spectroscopic observations of some CFSs in a 97″ diameter region centered inside the limb, observed on 2010 August 7, using IBIS (Cavallini 2006) at the Dunn Solar Telescope (DST) in Sunspot, NM. With IBIS we obtained spectral scans and sequences of single wavelength images (spectral resolution $R \sim 290{,}000$, spectral FWHM $\sim$ 22 mÅ) in H$\alpha$, between 14:18:45 and 14:33:32 UT. Figure 1 shows the full IBIS field of view with some rectangular areas demarcated for study below. Here we study a time series of images acquired at 0.1 s cadence over 100 s at a wavelength +0.11 nm from line center. The DST adaptive optics system was locked onto a small sunspot 22 arcsec inside the solar limb to correct seeing-induced wave front errors. We further processed IBIS images using speckle interferometric (Wöger et al. 2008) and multi-frame blind deconvolution (MFBD) techniques (Löfdahl 2002) to correct residual seeing-induced errors. The two methods produce images with essentially identical structures. We show here results using MFBD (with image contrasts adjusted to match speckle images), with a final cadence of 1 s.

Similar narrowband data have been obtained at the center of H$\alpha$ by van Noort & Rouppe van der Voort (2006) with a 0.3 s cadence, and Rouppe van der Voort et al. (2009) obtained H$\alpha$ profiles at 6.7 s cadence. Our conclusions will differ from those of these works because of the unusually fast changes we have observed in the wings of H$\alpha$.

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[3] The National Center for Atmospheric Research is sponsored by the National Science Foundation.

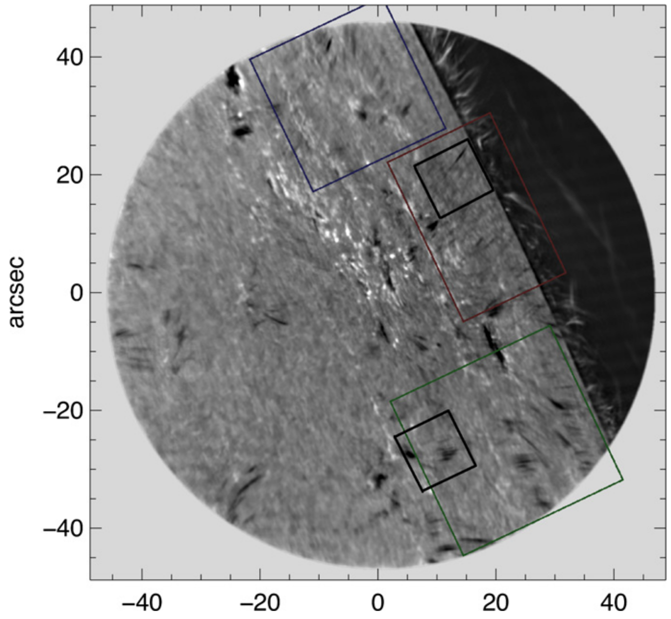

**Figure 1.** IBIS field of view, showing the sub-frames illustrated in Figures 2 and 3 (thick boxes) and in the three accompanying movies (thin colored boxes).

(Animations of this figure are available in the online journal.)

Figure 2 illustrates an example of CFSs manifested as dark thin structures visible in the wings of H$\alpha$. They are several thousand kilometers long, they are seen both to *appear and disappear along their entire length in a few seconds*. Within area (a), a narrow ($\Delta \lesssim 200$ km) CFS appears over a length $\ell \sim 3000$ km (half of the radius of the Earth!) between time steps 55 s and 58 s. These changes are certainly of solar origin. Seeing conditions were steady during the sequence, other CFSs show no concurrent variations, and bright features formed in the photosphere vary far more slowly. Phase speeds for propagation of any disturbance *along* this CFS would have to exceed 5000 km s$^{-1}$ to be compatible with the data from 55 to 57 s. Three movies accompany this Letter highlighting the other areas demarcated in Figure 1. They show that the very fast evolution shown in Figure 2 is not atypical, and that such phenomena often appear in groups, reminiscent of curtains blowing in the wind (area (b) in Figure 3). Three basic phenomena are seen in the movies: very fast changes in thin structures, often occurring in groups, as shown in Figure 2; apparently downflowing "blobs" moving near speeds of 50 km s$^{-1}$, probably related to "coronal rain" (e.g., Antolin & Rouppe van der Voort 2012); and relatively slowly evolving "fatter" features that remain present over the 100 s time series (example (c) in Figure 3). The first type seems to dominate in the first two movies, the third type is more prevalent in the third movie.

Given the unknown origin of CFS, the "cloud model" of Beckers (1964) suffices to examine origins of changes in the H$\alpha$ intensities $I_\nu$ in terms of a few physical parameters; the number densities $n_2$, $n_3$ of the $n = 2, 3$ levels of hydrogen (determining the line opacity and source function), the line width ($w$), and line Doppler shift ($s$). Assuming the source function is small compared with the photospheric intensity, and optical depths $\tau_\nu$ are $\ll 1$, then

$$\frac{dI_\nu}{dt} = -I_\nu^0\, a_{23}\, \Delta\left(\phi_\nu \frac{dn_2}{dt} + n_2 \left\{\left(\frac{\partial \phi_\nu}{\partial s}\right)_w \frac{ds}{dt} + \left(\frac{\partial \phi_\nu}{\partial w}\right)_s \frac{dw}{dt}\right\}\right). \tag{1}$$

Here, for simplicity, the thickness $\Delta$ is assumed constant; $a_{23}$ is the absorption cross section for H$\alpha$ radiation ($\propto$ oscillator strength), $I_\nu^0$ is the incident photospheric intensity, and $\phi_\nu$ is the absorption profile. Importantly, the parameters $n_2$, $w$, $s$, and $\Delta$ all respond on *dynamical* timescales to perturbations in the hydromagnetic state of the system,[4] since they are all functions of thermodynamic parameters (density, temperature, velocity) and non-local radiation fields.

The characteristic dynamical speeds of the H$\alpha$ absorbing plasma are not known, but upper limits can be strongly constrained as follows. The H$\alpha$ line must be formed in relatively cool, dense plasma near the coronal base, in a low-$\beta$ regime. It must be cool and dense to absorb radiation from the $n = 2$ levels, and it cannot be in a higher $\beta \gtrsim 1$ regime, since then the CFS would appear more turbulent, and less ordered, perhaps manifesting acoustic shock waves, quite unlike the observed behavior. When $\beta \ll 1$, dynamical changes are set by the Alfvén speed $C_A = (B)/\sqrt{4\pi\rho}$. (The sound speed $C_S$ is a mere 10 km s$^{-1}$ in chromospheric plasma.) $C_A$ is not known but tight constraints can be set using field strength measurements of $B < 50$ G obtained in spicules (Centeno et al. 2010), and mass densities characteristic of chromospheric plasma in which H$\alpha$ can form (Vernazza et al. 1981). For $\rho$ we use the ion plus neutral mass density in the last scale height of the chromospheric model "C" of Vernazza et al. (1981). (Proton–neutral ion collision times are of order milliseconds, far smaller than the dynamical timescales observed and of any observable Alfvén wave frequency; just using the ion density would increase $C_A$ by a factor $<2$.) With densities of $10^{11}$ particles cm$^{-3}$ $\rho \sim 2 \times 10^{-13}$ g cm$^{-3}$ a magnetic field strength $B \lesssim 50$ G gives $C_A \lesssim 300\,(B/50)\,((2 \times 10^{-13})/\rho)^{1/2}$ km s$^{-1}$. Super-Alfvénic dynamics can occur in strong shocks, but there is no evidence of any increase in brightness that should accompanying shock heating (intensity increases through emission line broadening, for example). We conclude that $\gtrsim$5000 km s$^{-1}$ apparent speeds cannot be accounted by physical transport of mass, momentum, and energy *along* this CFS element.

*Oblique* propagation of a wave with **k** vector at angle $\vartheta$ to the long axis of a pre-existing CFS tube could interact with it to produce arbitrarily high apparent speeds $\sim C/\cos\vartheta$, with $C=$ the wave phase speed. Consider waves originating from the photosphere. Spatially coherent waves have been observed at the top of the quiet internetwork chromosphere (e.g., Fleck et al. 1995; Wikstøl et al. 2000, at infrared and UV wavelengths, respectively), but these have periods two orders of magnitude larger than the changes reported here. Next, consider waves originating within the chromosphere and/or corona. To account for the rapid observed H$\alpha$ changes, propagation of the MHD fast mode ($C \sim C_A$) would need to occur within the **k** vector inside the narrow cone angle range $\cos\vartheta \lesssim 0.06$ or $\pi/2 - 0.06 \lesssim \vartheta \lesssim \pi/2 + 0.06$. But questions arise. Why, of all propagation directions, should those with a random probability of $0.12/\pi \sim 4\%$ be clearly visible (the example shown is just one of many in our data set)? What is the source of such waves? Would not the propagating wave front be subject to significant disruption through the inhomogeneous upper atmosphere? *Standing* waves can be discounted simply because they too take a time $\sim\ell/C_A$ s to set up, among other problems. We should see the standing wave develop long before the change in intensity

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[4] Individual H atoms can relax on timescales of level lifetimes, $10^{-8}$ s (Judge 2005). But, integrated over the observed volumes $V \sim \Delta^2\ell$, $\int n_2(t)dV$ varies on dynamical timescales at which plasma density and temperature vary throughout $V$, through collisional terms in the atomic rate equations.

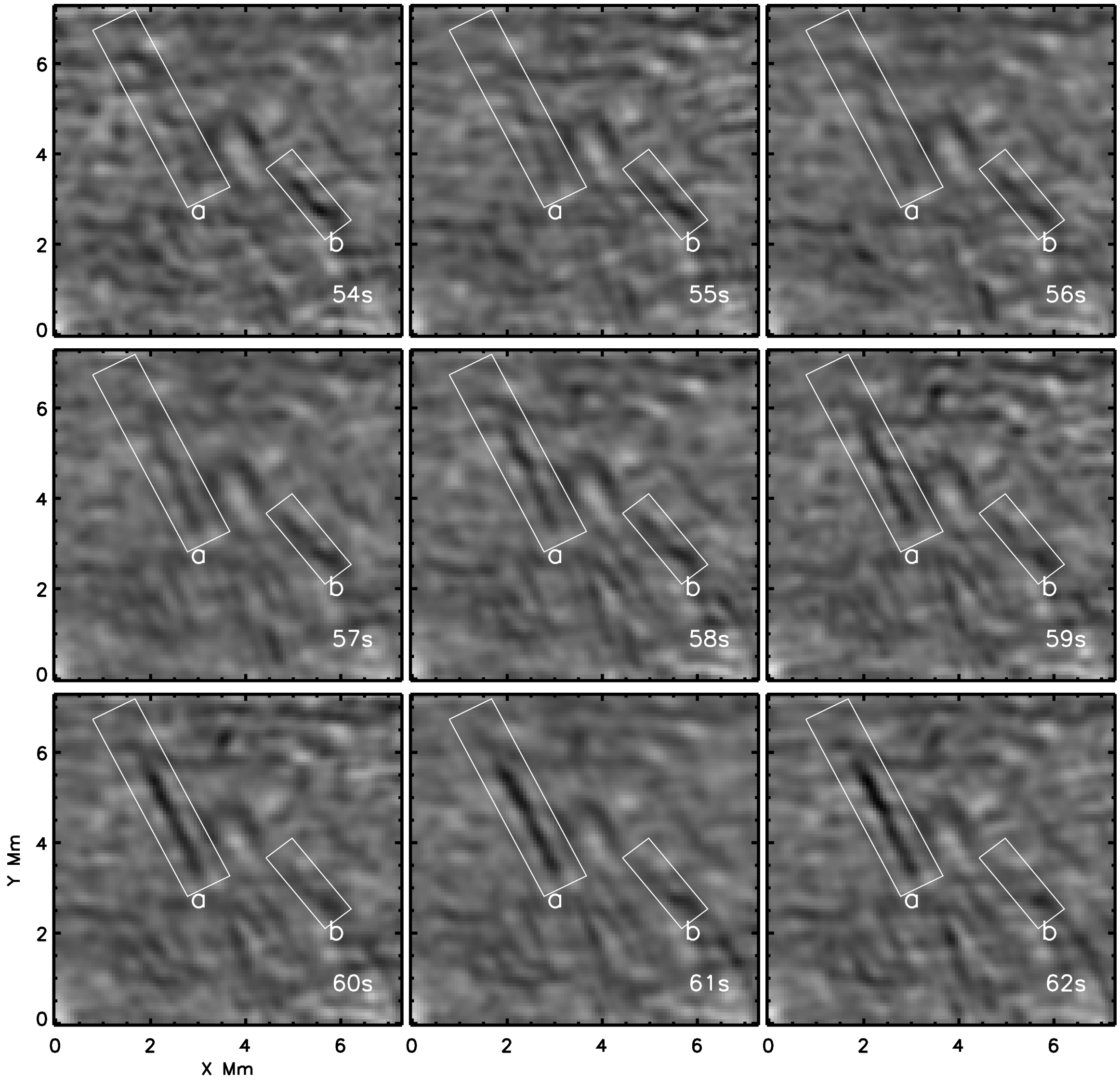

**Figure 2.** A 9 s long sequence of MFBD-reconstructed images in the red wing of H$\alpha$ observed with 1 s cadence, obtained with IBIS. Region (a) shows the appearance and region (b) the disappearance of dark features over several Mm (1 Mm = 1000 km) in a few seconds. The solar radius is 700 Mm, the area shown is just 30 millionths of the area of the solar disk area.

occurs, but it emerges out of "nowhere" (see the accompanying movies).

To avoid such contrivances, we follow the conjecture of Judge et al. (2011) to suggest that here we have found *first indirect evidence for the existence of plasma sheet structures in chromospheric plasma*. The movies that accompany this Letter reveal that CFSs often occur in clumps where they resemble the motions of curtains. Under this analogy, (sub-) Alfvénic motions in the otherwise continuous magnetofluid perturb the embedded plasma sheets in Parker's TDs to produce warps which, when aligned along the line of sight, result in the rapid appearance (or disappearance) of CFSs reported here. This picture appears *necessary* to explain our observations, for *some* certainly not *all* CFSs. Some sub-Alfvénic "dynamic fibrils" have a convincing explanation as a field-aligned flow (Hansteen et al. 2006).

Our proposal changes our notion of the building blocks of the solar outer atmosphere, and has consequential physical effects. Consider a cut through the plane perpendicular to a CFS. For a given volume of CFS plasma, circular cylinders have the smallest areas connected to the surrounding atmosphere, sheets have the largest areas. Kinetic transport across magnetic field lines (Athay 1990; Judge 2008) will be enhanced if some CFSs are sheets. The increased heat fluxes may help resolve at least three long standing problems: energy lost by radiation from the lower transition region greatly exceeds that transported down from the corona through field-aligned thermal conduction (Athay 1966, 1990; Gabriel 1976; Jordan 1980; Judge & Centeno 2008); the morphology of intensity images in the chromosphere and the transition region differs markedly from those of the corona (Feldman 1983; Judge 2008); remarkably, CFSs rarely expand systematically along their lengths, as a volume-filling plasma frozen to the magnetic field anchored in the photosphere must do. Cross-field energy transport from more volume-filling coronal emission into sheets might explain these problems.

In conclusion, at least some CFSs are better interpreted as line-of-sight integrations of two-dimensional sheets of plasma embedded in the three-dimensional magnetofluid. We speculate that the sheet plasma collects in TDs formed according to Parker's fundamental theorem of magnetostatics (Parker 1994).

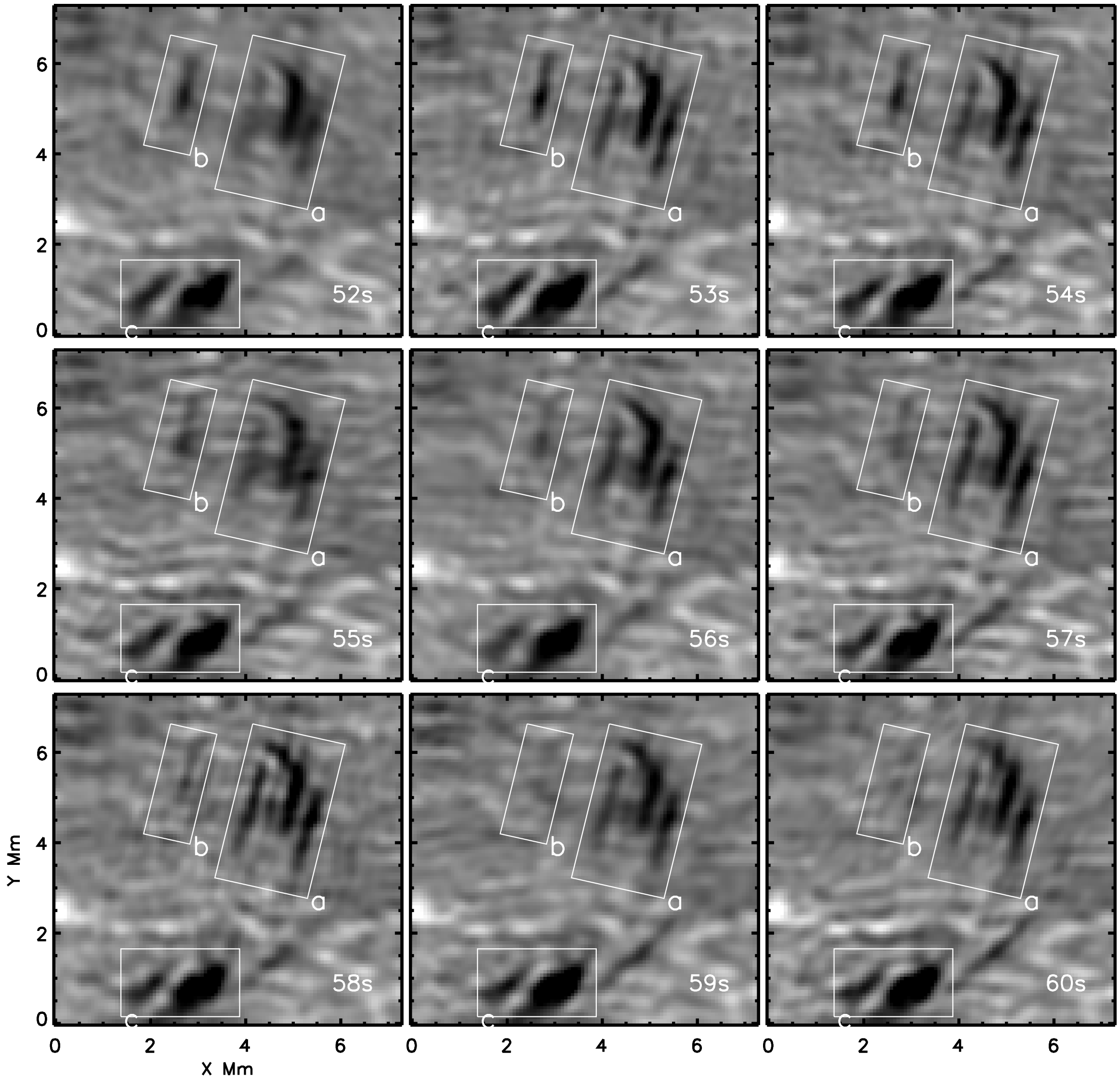

**Figure 3.** Another sub-frame shown as in Figure 2. Region (a) contains rapidly varying "curtains," region (b) a rapidly disappearing feature, and (c) relatively constant, "fatter" features.

Why that material is particularly visible in H$\alpha$ and on these particular spatial scales are observations as yet unexplained, but these problems are common to all CFS models. Regardless of their origins, the pervasive, rapid variations seen in the CFSs present a challenge to both observers and modelers to capture the intrinsic dynamics of the plasma. Further observations of this kind, at multiple wavelengths, should help disentangle the possible causes of such rapid variations reported here, with imaging spectrographs.

We thank B.C. Low and S. McIntosh for comments. P.G.J. thanks INAF and HAO for funds supporting a working visit to Arcetri Observatory in 2011.

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