Tracing the Topology of the October 18-20, 1995 Magnetic Cloud with ~0.1 - 10^2 keV Electrons

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Abstract. Five solar impulsive ~1-10^2 keV electron events were detected while the WIND spacecraft was inside the magnetic cloud observed upstream of the Earth on October 18 - 20, 1995. The solar type III radio bursts produced by these electrons can be directly traced from ~1 AU back to X-ray flares in solar active region AR 7912, implying that at least one leg of the cloud was magnetically connected to that region. Analysis of the electron arrival times shows that the lengths of magnetic field lines in that leg vary from ~3 AU near the cloud exterior to ~1.2 AU near the cloud center, consistent with a model force-free helical flux rope. Although the cloud magnetic field exhibits the smooth, continuous rotation signature of a helical flux rope, the ~0.1-1 keV heat flux electrons and ~1-10^2 keV energetic electrons show numerous simultaneous abrupt changes from bidirectional streaming to uni-directional streaming to complete flux dropouts. We interpret these as evidence for patchy disconnection of one end or both ends of cloud magnetic field lines from the Sun.

Introduction

Magnetic clouds are a type of coronal mass ejection (CME) in the solar wind characterized by relatively strong magnetic fields (low plasma beta) and a smooth rotation of the magnetic field direction over a ~1 day period at 1 AU, consistent with the passage of an approximately force-free helical magnetic flux rope of diameter ~0.25 AU [*Burlaga*, 1988]. They often exhibit CME characteristics such as enriched alpha particle content, low proton temperature and bidirectional electron streaming [*Gosling*, 1996], and there is evidence that perhaps most CMEs may be magnetic clouds (K. Marubashi, CME Chapman conference. [1996]). *Burlaga* [1991] and *Rust* [1994] suggest that magnetic clouds are the interplanetary manifestation of solar filaments (seen as prominences on the limb), which are often observed to have helical magnetic topology and to be embedded in CMEs. Alternatively *Gosling* [1990] suggested that 3-D magnetic reconnection across the legs of sheared arcades of coronal loops will result, after relaxation, in a magnetic cloud when the plasma beta is low. As pointed out by *Gosling* [1975] and *MacQueen* [1980] CMEs expel new magnetic flux, usually still connected to the Sun, into the interplanetary medium. Since the interplanetary magnetic field (IMF) magnitude is observed to stay roughly constant over time [*King*, 1979] compensating disconnection of IMF flux must occur.

Solar electrons from ~0.1 to ~10^2 keV are excellent tracers of the structure and topology of IMF lines since they are fast and have very small gyroradii. At energies from ~0.1 to ~1 keV, the continuous escape of hot coronal electrons forms the solar wind electron halo population, providing an outward heat flux from the Sun. At energies from ~1 to ~10^2 keV, the Sun often impulsively accelerates electrons in flare or coronal flare-like events (see *Lin* [1985] for review). As these electrons escape they produce solar type III radio bursts which can be tracked by spacecraft radio observations from the corona into the interplanetary medium and beyond 1 AU. Here we use observations of ~0.1 - ~10^2 keV electrons to trace the October 18-20, 1995 cloud's magnetic field lines back to the Sun, measure the length of these lines, and determine when the field lines are disconnected from the Sun.

Observations

Figure 1A, B, C shows $|\mathbf{B}|$, Θ_B, Φ_B, measured by the Magnetic Field Investigation (MFI) [*Lepping et al.*, 1995] on the WIND spacecraft located 176 R_E upstream of the Earth. The field rotates smoothly from south (Θ_B = -90°) to north (Θ_B = +90°) during the 30 hour passage of the October 18-20, 1995 magnetic cloud. Using the method of *Lepping et al*. [1990], we have fit this field to a right-handed force-free flux rope ($\nabla\times B = \alpha B$, with constant α) convecting past the spacecraft at the solar wind speed (~420 km/s). The cloud axis was determined to be nearly in the ecliptic plane (Θ_A = -7°) and close to the Archimedean spiral angle (Φ_A = 287°). Its diameter is about 0.28 AU, with WIND passing within ~0.03 AU of the axis at 1048 UT on October 19. These parameter values are very close to those obtained by *Lepping et al*. [1997].

The front of the cloud, identified with the passage of a tangential discontinuity in the magnetic field at 1858 UT on October 18, was preceded by a shock wave at 1037 UT (Figure 1D), about 8 hours earlier. Enhancements in He^{++} and bidirectional streaming of electrons are seen within parts of the cloud. The trailing edge of the cloud is not easily identified; we choose it to be at 0138 UT on October 20, coincident with the large dip in field strength and reversal in the field direction (Φ_B).

Assuming a constant, average solar wind speed of ~420 km/s (Figure 1D) the cloud is estimated to have left the Sun on Oct 14. *Smith et al*. [1997] identify the ejection with the GOES 1 - 8Å long duration soft X-ray burst beginning at ~0800 UT, which was accompanied by a moving type IV radio burst. The Yohkoh Soft X-ray Telescope (SXT) observed a dimming between active regions AR 7912 and AR 7913 at ~0830 UT [*H. Hudson, private communication to Smith et al.*, 1997] indicating that mass was lost along open field lines, followed by a gradual increase in X-ray intensity.

The WIND 3-D Plasma and Energetic Particle experiment provides observations of electrons from ~10 eV to ~300 keV, as well as of solar wind speed and density (Figure 1 D & E), with an array of double-ended semiconductor detector telescopes and electrostatic analyzers (see *Lin et al.* [1995]). Figure 1F shows the flux (F) of electrons streaming away from the Sun (135˚ - 180˚ pitch angles since Φ_A = 287˚) in 18 energy channels logarithmically spaced between ~0.14 and 110 keV. Several impulsive electron events with rapid onsets can be seen above 20 keV, for example, at ~2100 UT Oct 18, ~0600, ~1130 and ~1800 UT Oct 19. No impulsive events are detected with electrons streaming in the opposite direction (0-45˚ pitch angle). These events are detected down to ~1 keV electron energies [*Lin et al.*, 1996] with the faster electrons arriving earlier, characteristic of impulsive injection of the electrons at the Sun simultaneous at all energies, followed by escape along field lines out to 1 AU. This velocity dispersion is illustrated in Figure 1G, a color spectrogram of the ratio F/F_0, where F_0 is the average background flux in the absence of impulsive events.

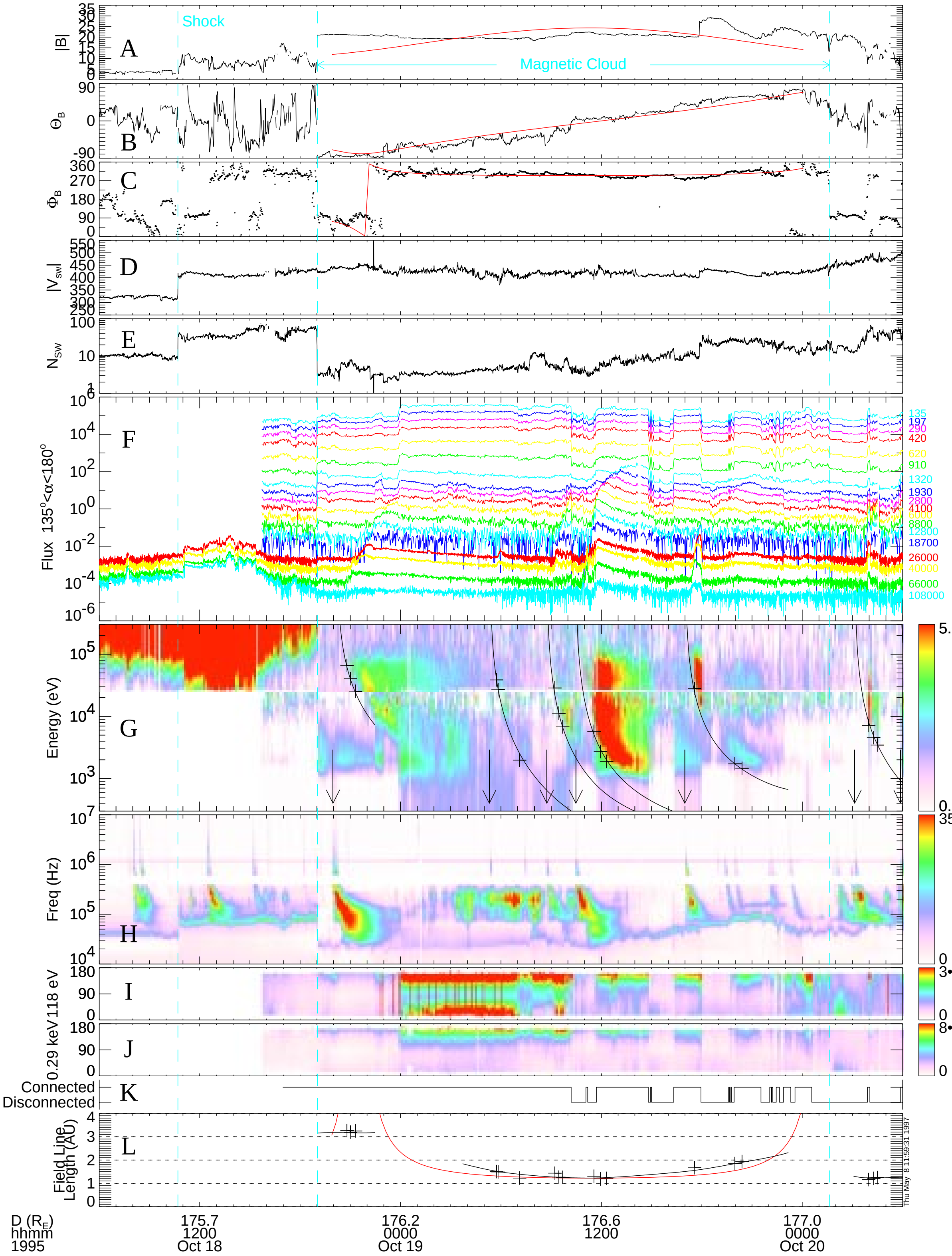

Figure 1. Summary plot of cloud event showing the magnetic field magnitude (|B|) and direction (Θ_B, Φ_B), (GSE coordinates), in panels A-C. Solar wind speed and density are shown in panels D &E. Panel F shows the electron flux for electrons traveling anti-parallel (135°<α<180°) to the magnetic field direction for 18 logarithmically-spaced energy channels ranging in energy from ~0.14 to 110 keV. The following spectrogram (panel G), presents the ratio, F/F_0, of electron flux (F) divided by an average background flux (F_0) measured in the absence of impulsive solar electron events. Panel H is a spectrogram of the radio observations from 10 kHz to 10 MHz from the WIND Waves experiment. Panels I & J are pitch angle spectrograms of electrons at 118 eV and 290 eV. Magnetic connection to, or disconnection from, the Sun along the negative leg of the cloud is indicated in panel K. From the flare time (arrows, panel G) and the arrival time of electrons as a function of energy, the field line length at each point was determined and is shown in panel L. The black curve in panel L is a smooth curve drawn by hand. The red curves in panels A, B, C & L show the expected values for a model flux rope (see text).

Such dispersion leads to electron beam distributions which are unstable to the production of electron plasma (Langmuir) waves. Those waves, in turn, produce solar type III radio emission at near the plasma frequency, f_p, or $2f_p$ (see *Lin* [1990] for review). The radio bursts drift from high to low frequency as the electrons propagate from the Sun to ~1 AU. Figure 1H is a color spectrogram of the radio observations from the WAVES instrument on WIND [*Bougeret et al.*, 1995]. As expected, the onset of each impulsive electron event coincides with a solar type III radio burst drifting down to near the local plasma frequency (~10-30 kHz). The high frequency (~14 MHz corresponding to a few solar radii) onset of each type III burst coincides with the time of a GOES 1 - 8Å soft X-ray flare. The Yohkoh SXT images show that all these X-ray flares occur within solar active region AR 7912 (Figure 2).

The crosses in Figure 1G mark the initial onset (at various energies) of the electrons in the impulsive events. Using the start of the solar type III burst at high frequencies as the electron injection time at the Sun, the field line length ($L = v_{el} \bullet \Delta t$) traveled by the electrons was computed (Figure 1L). This varies from ~3 AU near the leading edge of the cloud to ~1.2 AU near the center and rises again on the trailing part.

Figure 1 I & J shows pitch angle spectrograms of 118 eV and 290 eV halo (heat flux) electrons. Early in the cloud (~1900 UT Oct 18 - 0700 UT Oct 19), bidirectional streaming of these electrons is observed (this is not apparent before 0000 UT Oct 19 in the Figure because the fluxes are low). The fluxes are comparable below ~200 eV but not above, consistent with both ends of the cloud field line being connected back to the solar corona, but to regions of different coronal temperature. After ~0700 UT Oct 19, the electrons are generally uni-directional, indicating magnetic connection to the corona along only one leg of the cloud, but there are also many abrupt, discontinuous drops in electron fluxes (e.g. ~1010-1130 UT, 1500-1615 UT, 1800-1930 UT on Oct. 19). The pitch angle spectrograms (Figure 1 I & J) show these to be heat flux dropouts (HFDs) which *McComas et al.* [1989] suggested are due to disconnection of the IMF from the corona. Almost all these dropouts extend up to high energies and are observed in the impulsive events as well, confirming that these are times when the magnetic field is truly disconnected from the Sun, unlike many of *McComas et al.'s* HFDs which were not dropouts above 2 keV [*Lin and Kahler* 1992]. These disconnected regions (Figure 1K) range from a few minutes to hours long and are intertwined with connected regions.

Discussion

The solar impulsive electron events observed inside this magnetic cloud provide new information on the cloud's origin and magnetic topology. The tracking by the type III radio bursts of these electron events from ~1 AU back to X-ray flares at the Sun provides the first direct identification of the footpoints of the magnetic fields of a cloud. The electrons accelerated in solar active region AR 7912 clearly have direct access to the negative (field pointing into the Sun) leg of this cloud (see Figure 2).

Assuming a cylindrical flux rope with a diameter of 0.28 AU, the total magnetic flux within the magnetic cloud is estimated to be $\sim 1 \times 10^{13}$ Webers, compared to $\sim 4 \times 10^{13}$ Webers for the negative polarity sunspot region of AR 7912 and $\sim 17 \times 10^{13}$ Webers for the entire negative polarity region between AR 7912 and AR 7913 (estimated from the Kitt Peak magnetogram for October 14, the day the cloud left the Sun). Thus, ~6 to 25% of the total flux is ejected in the cloud.

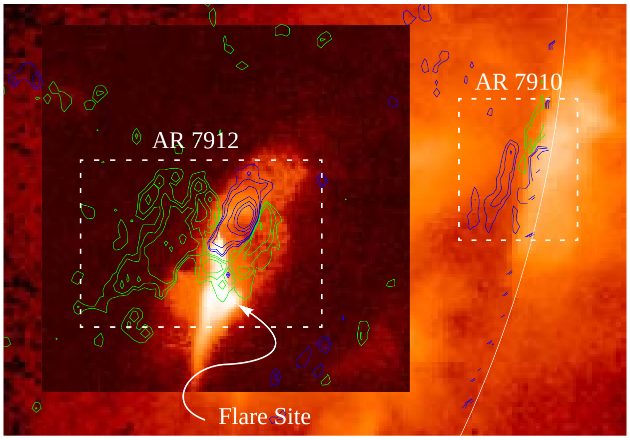

Figure 2. Short exposure SXT image of flare at 1030 UT, Oct. 19, 1995 with superimposed Kitt Peak magnetogram contours (adjusted to time of flare). Negative magnetic polarity contours are blue; positive contours are green. A portion of the full disk image is shown in the background.

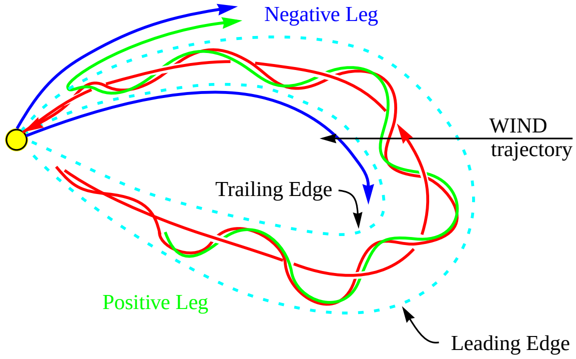

Figure 3. Schematic picture of possible magnetic cloud topology. In a magnetic flux rope with constant alpha, magnetic field lines wind around a central core axis in a helix pattern. Two closely spaced field lines of a magnetic flux rope are shown. These two field lines are nearly parallel but one is connected to the Sun along the negative leg, whereas the other is not.

By arbitrarily modeling the variation of the flux rope radius with distance L along the axis as $R(L)=R_0\sin(\pi L/2L_0)$, and assuming conservation of magnetic flux and current, we find that the tangential and axial components scale as $B_T \propto R^{-1}$ and $B_A \propto R^{-2}$, and the total length L_T of a helical field line at radius r from the axis at distance L_0 (total length along axis is $2L_0$ from end to end) is:

$$L_T(r, L_0) = \int_0^{L_0} \sqrt{1 + \left(\frac{B_T(r, L_0)}{B_A(r, L_0)} \cdot \sin\left(\frac{\pi}{2}\frac{L}{L_0}\right)\right)^2}\, dL$$

This (red curve in Figure 1L) is qualitatively consistent with the field line lengths determined from the electron arrival times (crosses). The 3 AU length of the outer field line compared to ~1.2 AU near to the axis implies in this model that it undergoes ~4 turns from the Sun to 1 AU, or ~8 turns for the entire cloud assuming symmetry. The number of turns should be invariant if the field has not been magnetically reconnected while propagating from the Sun to 1 AU. The implication is that the flux rope was highly coiled at the time of ejection from the Sun.

Figure 3 is a schematic representation of the cloud topology, with magnetic field lines connected to the Sun on both ends, on one end, and completely disconnected, intertwined together. The disconnections presumably result from magnetic reconnection near the Sun. Since the HFDs are observed simultaneously across all electron energies, the disconnections must have occurred > 6 hours earlier (the travel time to 1 AU for the slowest electrons). Furthermore, the flux of energetic (20 keV/nucleon) ions (from the Energetic Particle: Acceleration Composition and Transport (EPACT) investigation on WIND [*von Rosenvinge et al.*, 1995]) shows coincident dropouts, implying the disconnections occurred as much as ~20 hours before the HFDs are detected at 1 AU.

Gosling et al. [1995] have argued that magnetic clouds are formed by 3-dimensional reconnection of sheared magnetic arcades, and that, in the process, a mix of field lines connected at one end, at both ends and completely disconnected from the Sun can be produced. Alternatively, the cloud could also have emerged from the solar surface and been ejected from the Sun as a fully evolved flux rope with little or no reconnection. We believe the disconnections probably occurred after the ejection of the cloud from the Sun ~4 days earlier; otherwise the magnetic tension forces might be expected to significantly distort the cloud. As the cloud moves through the interplanetary medium, the legs of the flux rope may become partially disconnected from the solar surface through magnetic reconnection with adjacent field lines. Evidence for this is provided by an interplanetary type III radio storm detected by the WIND WAVES experiment in 2.0-5.0 MHz range following the ejection of the cloud and prior to its detection at 1 AU. Such storms are believed to be the result of magnetic reconnection of magnetic fields high (~1 R_S) in the solar corona [*Bougeret et al.,* 1984].

Magnetic clouds with many impulsive electron events appear to be rare; of the ~10 observed by WIND in the first 24 months, only one other cloud (on Feb. 8, 1995) had an impulsive electron event. This was the only other event to show HFDs as well.

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