The Radial Expansion of Magnetic Clouds

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Introduction

While our studies with a non-force-free model of magnetic ropes clearly shows that the ropes are often nearly force-free, our data also indicates that these magnetic ropes expand as they move outward from the Sun. This expansion can be inferred from the "temporal" asymmetry in the magnetic field profile. Often the ropes exhibit a much faster rise in field strength as they cross the spacecraft than the later fall in magnitude. Since our model and those of other groups when applied to a single spacecraft's data assumes cylindrical symmetry, we resort in our model inversion to use an "expansion" parameter to account for this asymmetry. An alternate approach of normalizing the components of the field by the field strength is less desirable because the rise and fall in field strength signals the pressure gradient in the field that balances the curvature force of the rope. Thus such normalization prevents the true force balance in the rope to be discerned.

Even with a single spacecraft one can confirm that flux ropes expand with radial distance using a statistical approach if that spacecraft is in an elliptical heliocentric orbit and covers a range of radial distances from the Sun. Wind, ACE and Pioneer Venus could not provide such data. However, Helios 1 and 2 could and Bothmer and Schwenn [1994] were able to show that flux rope diameters scaled as $R^{0.78 \pm 0.10}$ where R is the distance from the Sun. In our studies we have been able to obtain examples of two spacecraft measurements of the same flux rope and herein we exploit those data to verify this statistical relationship in individual cases.

The model we use has been described by Mulligan and Russell (2000). Herein we use its cylindrically symmetric form illustrated in Figure 1a. The axial field scales as a negative exponential of the distance from the center of the rope to a power. The power and the scale length of the fall off are both parameters of the fit. The axial field is proportional to one minus a negative exponential raised to a power. Again the power and the scale length of the exponential fall off are independently fitted in the inversion. Other parameters include the impact parameter of the rope crossing, the direction of the rope axis and an expansion factor.

One of the outputs of this process is shown in Figure 1b, a plot showing the orientation of the rope in "three dimensions" with the can delineating the outside of the rope and the axial field line drawn back to the Sun. In our multisatellite studies we are attempting to capture a rope at two locations R_1 and R_2 as sketched in Figure 1c where the rope has radii, r_1, and r_2. Since a rope will preserve its total magnetic flux as it expands, some simple assumptions as sketched in Figure 1d can give us some estimates of how fast the poloidal and axial fields will vary as the rope moves away from the Sun. We calculate that roughly the rope radius should change proportionally to distance from the Sun, a value not greatly different than the value found statistically by Bothmer and Schwenn [1994].

Verifying the Procedure

On January 7, 1998 NEAR was heading toward a gravity assist with the Earth when an ICME crossed it and the ACE spacecraft when they were separated by 0.05 AU radially and 0.02 AU azimuthally. The magnetic field data and the best independent fits to the data are given in Figures 2a and 2b and the currents are shown in Figures 2c and 2d. The directions of the axes of the rope obtained from the two fits differ by only 6° in cone angle (62° vs 56°) and 5° in clock angle (15° vs 10°). Both fits returned a flux content of 10 TWb and a left-handed rope. The impact parameters are 0.16 for Wind and 0 for NEAR. Both ropes are force-free except near the outer edge of the rope. While the peak parallel currents are similar the rope at Wind has a much lower parallel current near the center. If the current normalized by the field strength (which is fairly constant here) is constant, we refer to this as being in the Taylor state. Thus the rope at NEAR is closer to the Taylor state than the rope at Wind.

The Bastille Day Event

In mid July 2000 when NEAR was aligned almost radially with the Earth, a very strong ICME termed the Bastille Day event crossed ACE and later NEAR. The magnetic field data are shown at ACE and NEAR in Figures 3a and 3b, together with a fit in which the same rope was allowed to expand arbitrarily as it moved from ACE to NEAR. The currents obtained from this fit are shown in Figures 3c and 3d. The dashed lines show a snapshot of the rope at a fixed time. The radius has changed from 0.25 AU to 0.43 AU over 1.76 AU. Thus the radius varies as $R^{0.96}$ slightly higher than Bothmer and Schwenn's [1994] $R^{0.78 \pm 0.10}$. Table 1 gives the parameters of the fitting procedure treating each fit as totally independent, by adopting an expected fall off and fitting simultaneously and by fitting with an arbitrary fall off. We see all three approaches give similar results.

Table 1. Characteristic and Integrated Parameters of Flux Rope Model Fits for July 15-17, 2000 Magnetic Cloud

	Independent Fits		Simultaneous Fits		Free Expansion Fits	
Property	ACE	NEAR	ACE	NEAR	ACE	NEAR
Handedness	L	L	L	L	L	L
Clock Angle (q)	53°	48°	50°	50°	50°	50°
Cone Angle (F)	92°	76°	83°	83°	83°	83°
Radius, AU	0.24	0.43	0.25	0.43	0.25	0.43
Flux, 10^{12} Wb	95	137	108	130	118	158
Total Current, 10^6 A	72	97	66	79	97	85
Twist (a*), mA/Wb	0.76	0.72	0.60	0.60	0.72	0.63
N_T	0.28	0.47	0.22	0.41	0.28	0.41
Impact Parameter, AU	0.10	0.16	0.11	0.17	0.10	0.16
Expansion Factor g	0.66	0.35	0.50	0.50	0.73	0.73
B_a Expansion law, R^{-x}	2	2	2	2	1.4	1.4
B_p Expansion law, R^{-x}	2	2	2	2	1.2	1.2
B_a Spread	0.71	0.87	0.71	0.71	0.81	0.81
B_p Spread	0.75	0.06	0.53	0.53	0.53	0.53
B_a Exponential Power	2.4	2.7	2.5	2.5	2.5	2.5
B_p Exponential Power	1.7	2.8	2.1	2.1	2.0	2.0

The August 13, 2000 Event

On August 13, 2000 NEAR was 15° east of the Earth-Sun line and at 1.72 AU from the Sun when an ICME crossed ACE and then NEAR. Figures 4a and 4b show the observed and fitted magnetic field profiles for this event and Figures 4c and 4d show the currents. The rope appears to be nearly force-free in the central regions but decidedly non-force-free at the edges. Here we show the "free expansion" fit which allows the magnetic field and scale of the rope to have an arbitrary fall off. The size of the rope is found to vary as $R^{0.84}$ a value quite consistent with the results of Bothmer and Schwenn (1994). Table 2 gives the results of the fitting procedure in three ways: treating each fit as independent, by adopting an expected fall off, by fitting simultaneously, and by fitting with an arbitrary fall off. All three techniques give similar results for most parameters.

Table 2. Characteristic and Integrated Parameters of the Flux Rope Model Fits for the August 13-15, 2000 Magnetic Cloud

	Independent Fits		Simultaneous Fits		Free Expansion Fits	
Property	ACE	NEAR	ACE	NEAR	ACE	NEAR
Handedness	L	L	L	L	L	L
Clock Angle (q)	83°	62°	78°	68°	78°	68°
Cone Angle (F)	102°	97°	105°	98°	105°	98°
Radius, AU	0.17	0.29	0.17	0.29	0.17	0.29
Flux, 10^{12} Wb	38	41	37	36	41	40
Total Current, x 10^6 A	141	69	47	47	79	79
Twist (a*), mA/Wb	3.71	1.70	1.29	1.32	1.92	1.95
N_T	1.38	1.10	0.47	0.85	0.72	1.26
Impact Parameter, AU	0.01	0	0	0.01	0.01	0.06
Expansion Factor g	0.34	0	0.17	0.17	0.23	0.23
B_a Expansion law, R^{-x}	2	2	2	2	1.8	1.8
B_p Expansion law, R^{-x}	2	2	2	2	1.3	1.3
B_a Spread	0.81	0.87	0.87	0.87	0.83	0.83
B_p Spread	3.2	0.77	0.79	0.79	0.89	0.89
B_a Exponential Power	9.6	2.2	3.2	3.2	3.0	3.0
B_p Exponential Power	1.7	0.89	1.1	1.1	1.2	1.2

Event Summary

The similarity of the two independent inversions of the January 7 event as observed by Wind and NEAR suggest that our independent inversions are accurate or at least consistent. In Figures 5a and 5b we show the geometry that we obtain from these independent cylindrically symmetric fits for the July and August 2000 events. The July event clearly shows the expansion of the rope with radial distance. For the August event in we have propagated the ACE event to close to NEAR's heliocentric location to illustrate that the bend in the rope axis appears to be significantly less than predicted by our dipolar extrapolation of the axial magnetic field.

Figure 1d can be used to estimate the expected radial expansion of a cylindrically symmetric force-free flux rope. First in a cylindrically symmetric force-free rope we expect the outward magnetic pressure of the rope (that we approximate by the axial field squared) to be balanced by the cross terms in the magnetic stress, which we approximate by the product of the axial and poloidal fields. Then we note that the conservation of magnetic flux tells us that the axial field varies inversely as the radius of the rope squared and the poloidal field varies inversely as the product of the radius of the rope and the distance to the Sun. This latter relationship allows us to relate the radius of the rope to the heliocentric distance and show that the expected variation of the rope size with radial distance is roughly proportional to R. This is in fact close to the number we see.

If the ropes are oval in cross section the results would not be too different. Figures 5c and 5d show the expansion expected of oval ropes whose cross flow dimension expands so as to subtend a constant angle at the Sun. Since this cross flow dimension also varies as the heliocentric distance for constant angle expansion, there should be no change in the expected radial expansion exponent.

Lessons for STEREO

STEREO provides measurements at a constant heliocentric distance. Thus it will have to depend on fitting asymmetries in the magnetic profile and examining the temporal variation in the flow velocity to deduce the expansion of the rope as it passes. STEREO will, however, do a much better job of defining the bending of the axes of ropes that lie in the ecliptic plane and of measuring the cross-flow dimension of ropes whose axes are perpendicular to the ecliptic plane. The gradual separation of the two STEREO spacecraft will allow us to probe ICMEs at slowly increasing impact parameters over at least the first full year of the mission.

Acknowledgment

References

Bothmer, V. and R. Schwenn, Eruptive prominences as sources of magnetic clouds in the solar wind, *Space Sci. Rev.*, 70, 215-220, 1994.
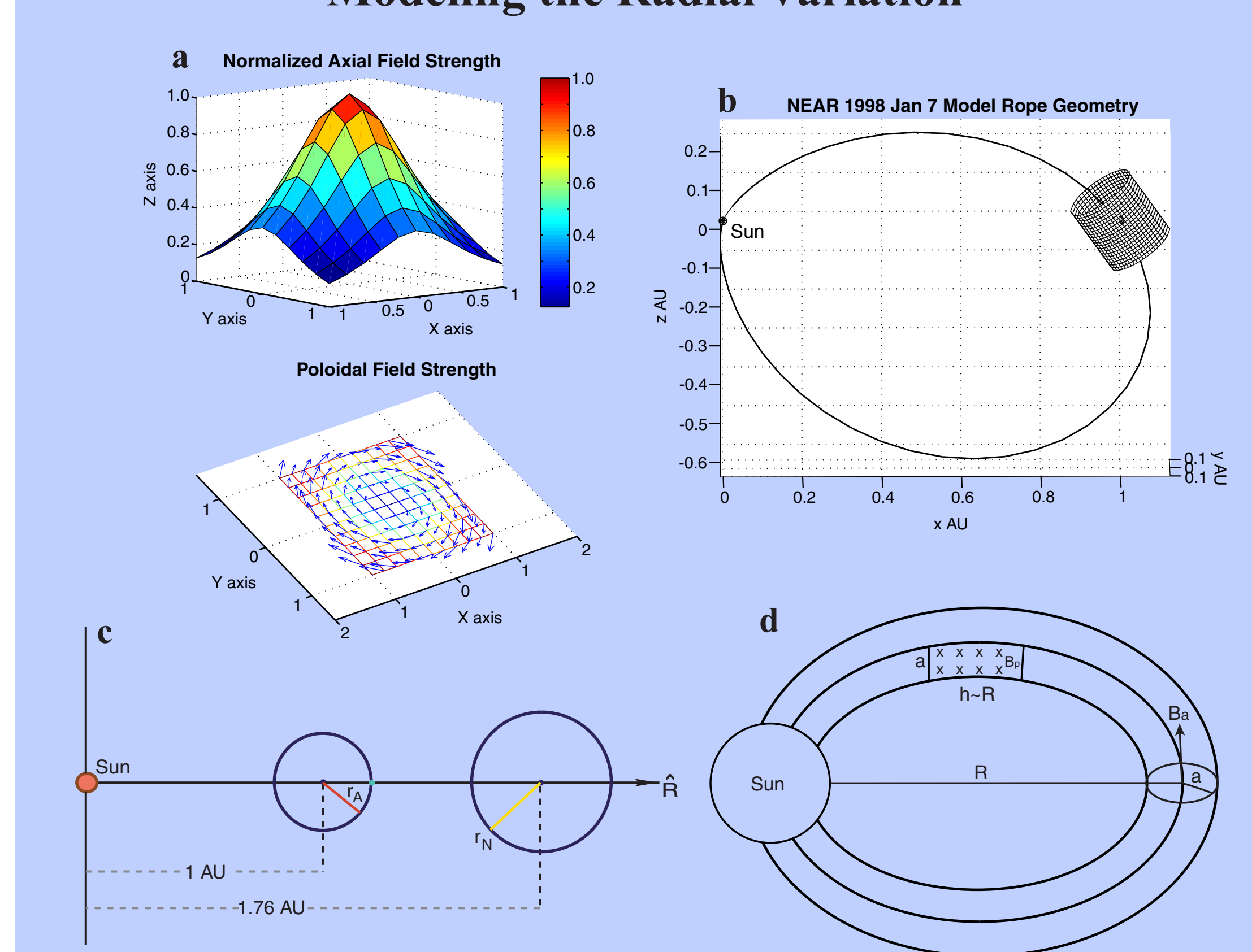
Modeling the Radial Variation

Figure 1. Modeling the radial variation of flux ropes. a) The cylindrically symmetric model. b) An independent fit to January 7, 1998 rope. c) Snapshot of rope connections at two radial distances. d) Schematic illustrations of rope connected to sun.

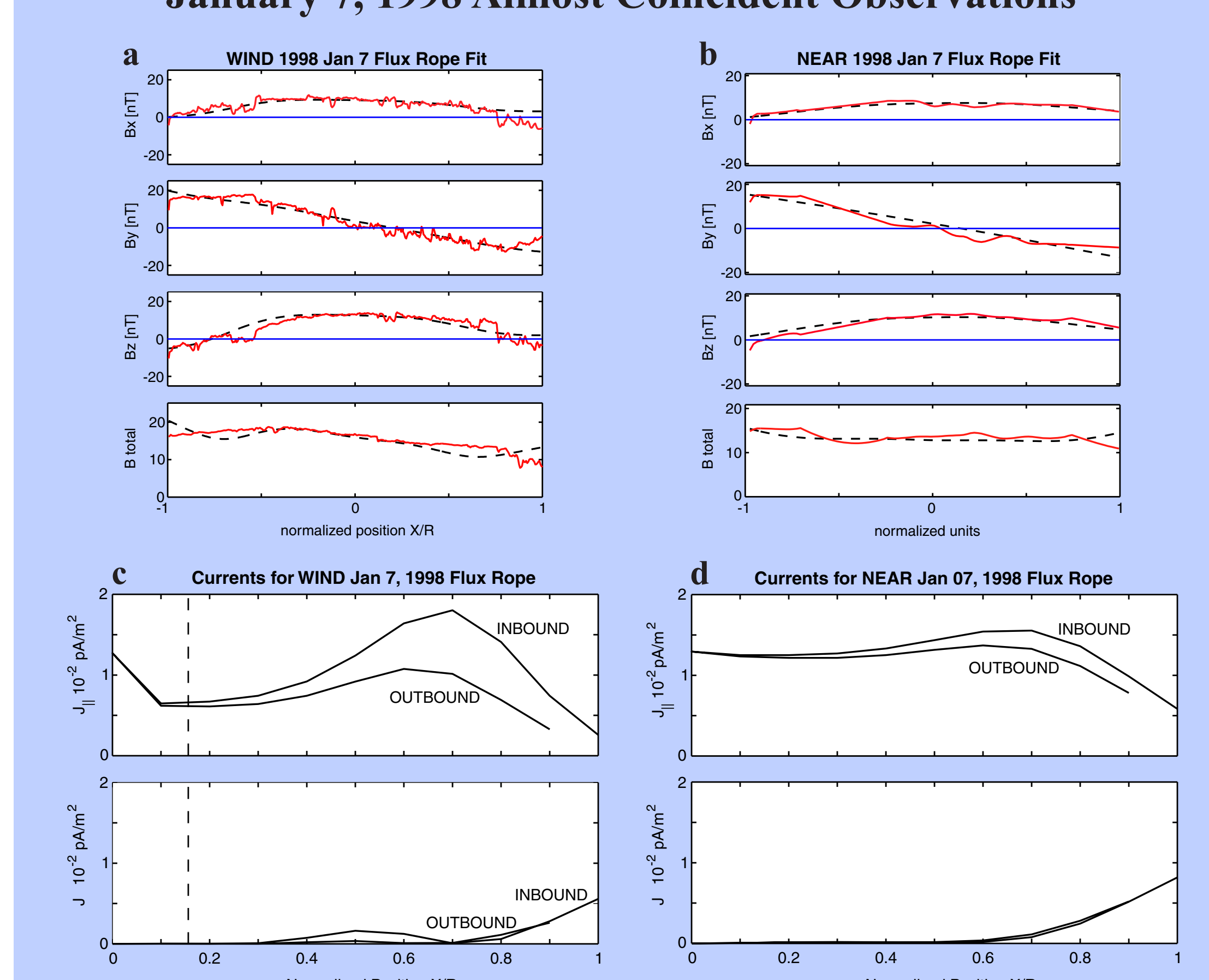### January 7, 1998 Almost Coincident Observations

Figure 2. Fields and modeled currents seen by WIND and NEAR on January 7, 1998 when the spacecraft came separated by less than 0.02AU, azimuthal showing similarity of independent fits.
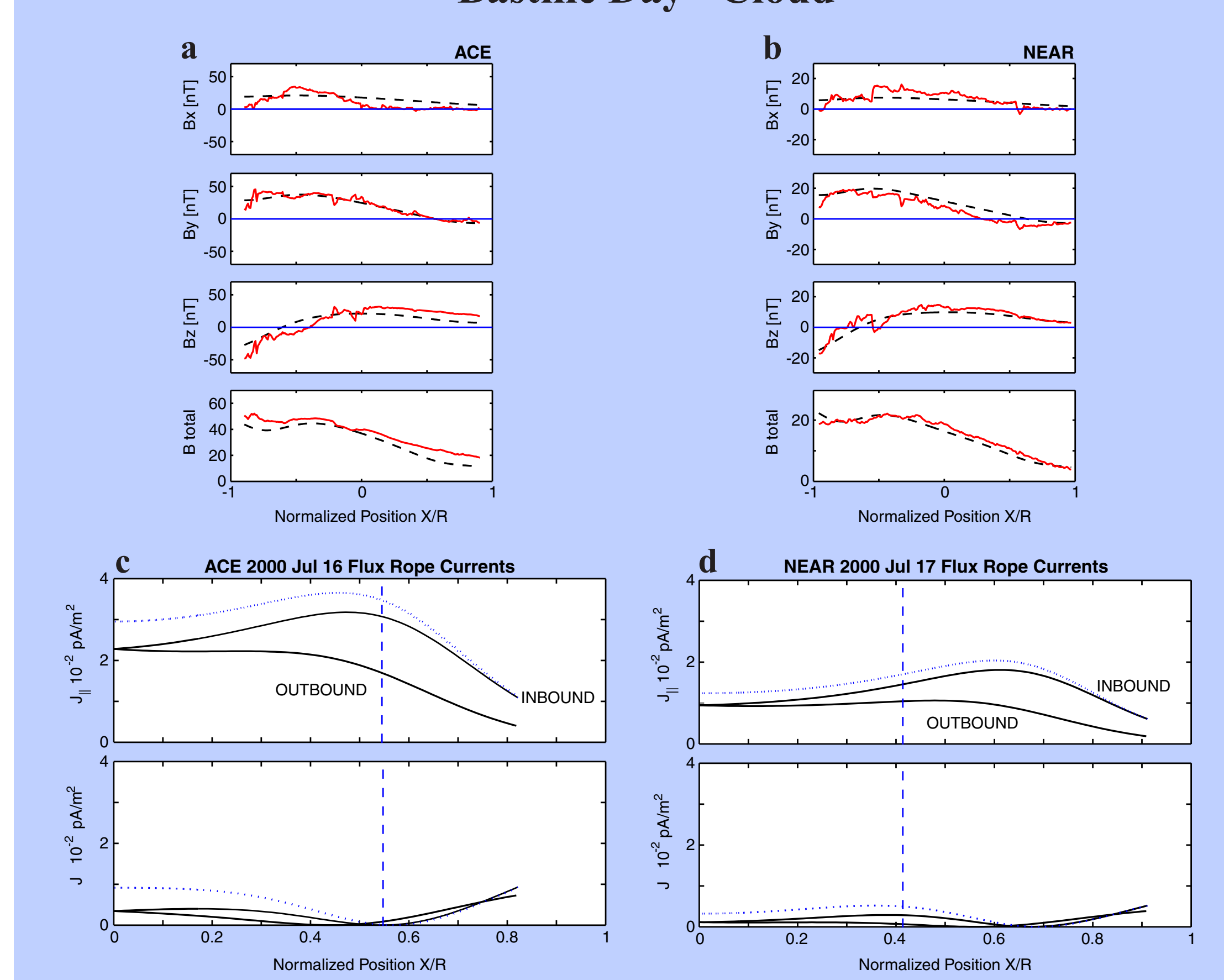
"Bastille Day" Cloud

Figure 3. Fields and modeled currents for simultaneous fit to Bastille Day cloud. a) ACE magnetic field. b) NEAR magnetic field. c) ACE currents. d) NEAR currents. Vertical dashed line shown the impact parameter. Horizontal dashed line shows a snapshot of current with expansion removed.
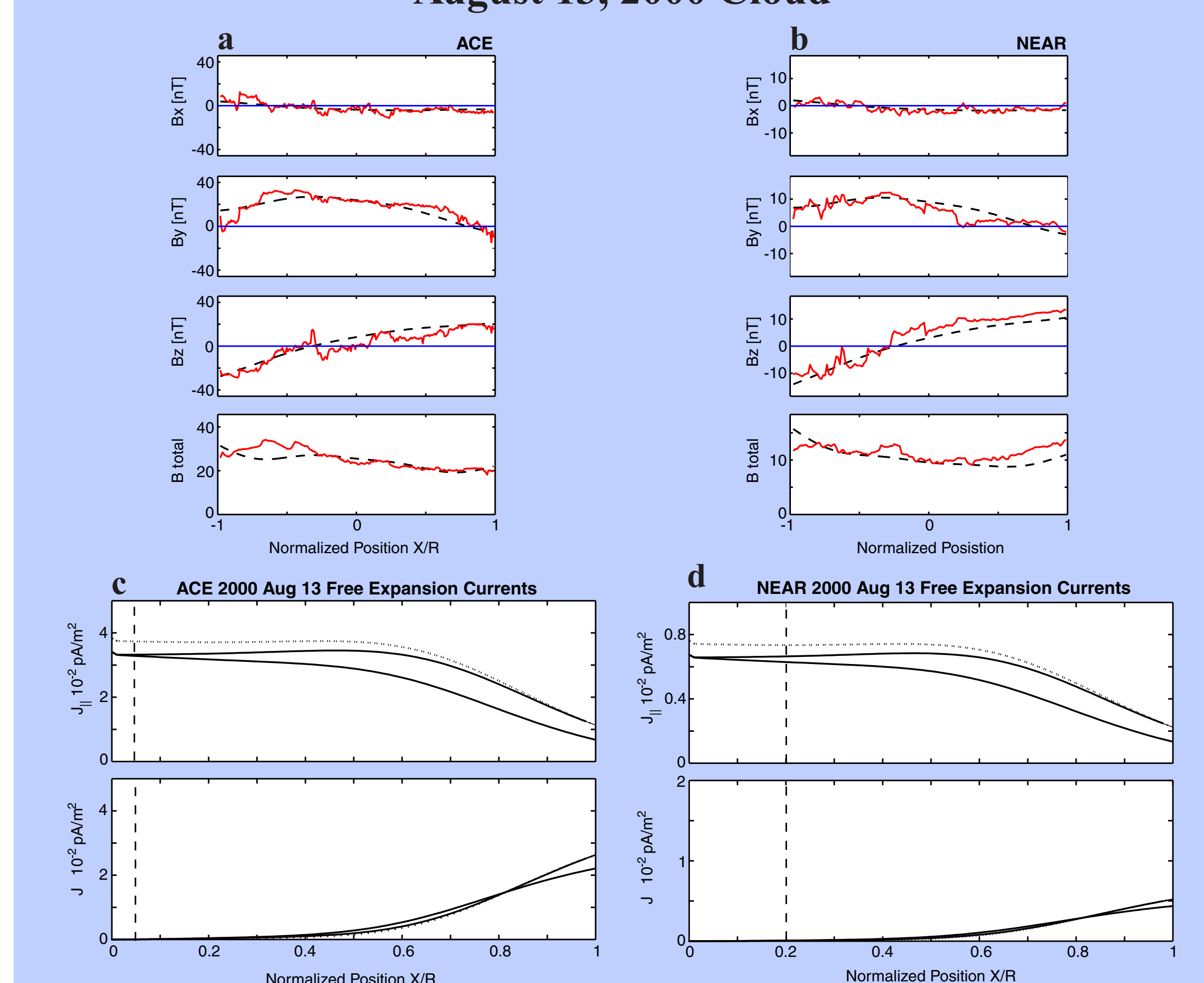
August 13, 2000 Cloud

Figure 4. Fields and modeled currents for simultaneous fits to August 13, 2000. cloud a) ACE fields. b) NEAR magnetic fields. c) ACE currents. d) NEAR currents. Vertical dashed line shows impact parameter. Horizontal dashed line shows a snapshot of current with expansion removed.
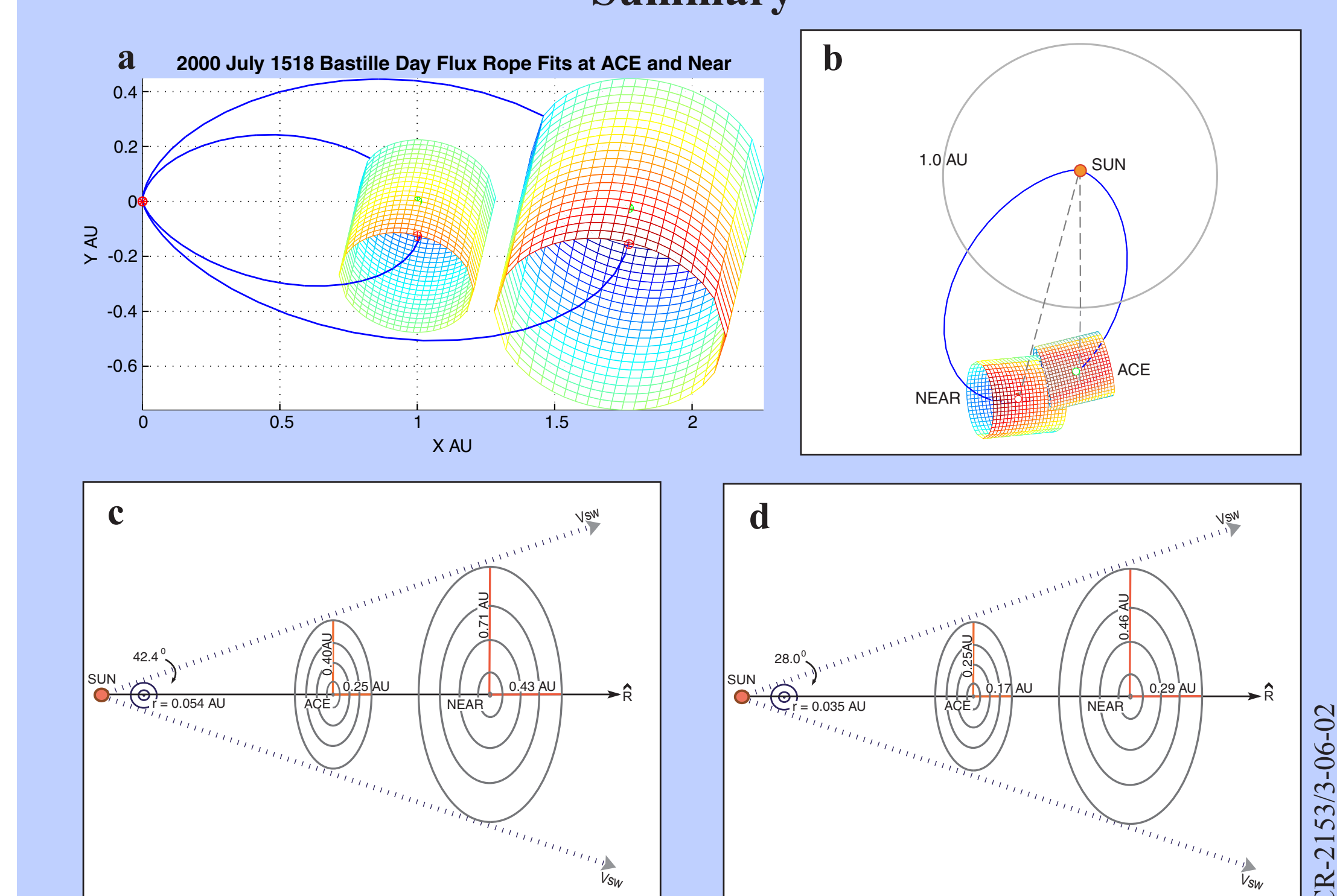
Summary

Figure 5. Summary of expanding ropes. a) Cylindrical fit to Bastille Day cloud. b) Cylindrical fit to August 13, 2001 cloud. c) Inferred 2-D expansion of Bastille Day cloud. d) Inferred 2-D expansion of August 13, 2001 cloud. (not to scale)

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