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Electron diffusion region and thermal demagnetization

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[1] The demagnetized skin depth width electron diffusion region (EDR) distinguishes the innermost current layers of collisionless magnetic reconnection (CMR) from other current layers. Such narrow layers with virtually unknown properties are hard to identify in space observations. Soon, diagnosing it will be the central focus of NASA's Magnetospheric Multiscale Mission. Initial attempts have been made to frame necessary tests to ensure that the observer is in the EDR. Since none of the tests are sufficient to identify the EDR, it is important to vet as many necessary conditions as possible. In this way a winnowing process can lessen the likelihood of false positive detections of the EDR. Since the "necessary" criteria of the EDR are usually not amenable to direct experimental tests, a vetting process is desirable before accepting "necessary" proxy tests for the criteria of CMR. This paper proposes a further necessary test of an essential property of the EDR: the necessity that the thermal electrons be demagnetized in these regions. Without this attribute, the magnetic flux is essentially frozen to the electron fluid velocity and the topology breaking of CMR is thwarted. We have framed this test from kinetic theory, gathered the relevant observables, and used it with a published set of over 100 previously identified EDRs. Surprisingly, 99% of them are $\simeq$100 times more magnetized than expected for the EDR of CMR theory. The outcome of this falsifiable test demonstrates the scientific dialogue is incomplete for framing adequate pragmatic tests for identifying EDRs.

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1. Introduction

[2] This paper continues a dialogue started by *Mozer* [2005] (hereafter paper 1) about how to find the electron diffusion region (EDR) of collisionless magnetic reconnection (CMR) in space plasma data. Our purpose is to understand how, with high confidence, one could screen a given time series for the possibility that it was a traversal of the highly elongated but thin EDR recently documented [*Daughton et al.*, 2006; *Karimabadi et al.*, 2007; *Scudder and Daughton*, 2008], the modern substitute for the "X" in the usual cartoon of magnetic reconnection.

[3] To set the stage for our contributions to this dialogue we paraphrase the six criteria previously used (paper 1) as a conceptual sieve for EDR layers. In most cases the criteria are derivable from analytical work that has been done concerning reconnection. Among these are (1) that $\mathbf{B} \times \nabla \times \mathbf{E}_{\parallel} \neq 0$ [e.g., *Longmire*, 1963]; (2) the width of the current channel along the stagnation streamline should have the electron skin depth d_e, scale [*Vasyliunas*, 1975]; (3) that (Joule) electromagnetic energy should be deposited in the plasma as a result of the reconnection; (4) that the plasma at the site of this deposition should have received this energy; and (5) that there should be a change of magnetic topology centered at this layer. To this canonical list, one further criterion was added by paper 1: (6) that $E_{\perp}$ in the EDR should be sufficiently large and "disruptive" to make the EDR have a significant effect on the overall dynamics. The pragmatism of what is observable was folded with these criteria to formulate algorithmic tests of observables that were used as necessary preconditions for satisfying the conceptual criteria. Certifying that $E_{\parallel} \neq 0$ was used as a test of this type for the first condition. The transit times and canonical magnetopause speeds were used to estimate compliance with the second criterion. Estimates of the positivity and large absolute size of $\mathbf{J} \cdot \mathbf{E}$ were screened for the third criterion. The change of topology screen was implemented in terms of there being a change (in sign) of the components of $\mathbf{E} \times \mathbf{B}$ transverse to the normal upon traversing an EDR layer. The "disruptive" criterion was said to be satisfied when $E_{\perp}$ was much larger than a further proxy for the asymptotic reconnection electric field, namely, $E_{\perp} \gg 0.1\ V_{Ai\infty}\ B_{\infty}$.

[4] This approach with the 6 screens attempted to winnow events with necessary conditions, recognizing that none of the suggested necessary pragmatic tests was sufficient for the identification. A difficulty with formulating a set of screens from a data set and then organizing the same data set with these screens is that there is no orthogonal test that can comment on the integrity of the filtered result from the sorting process. In this sense a tautology will not be

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found, and the intersection set of all conditions is occupied. The output of such a process becomes by definition what it is said to be. In the case of paper 1, those events which passed the six tests were "defined" to be electron diffusion regions. Apart from fulfilling the 6 tests, what additional property is singular about the events that pass and do not pass the screening? Paper 1 gave a brief statistical summary of context variables (not used in the selection process) at the selected "EDR" sites, but did not use them to evaluate or comment on the screening efficacy of the 6 screen test.

[5] The plan of this paper introduces the seventh sieve for the EDR (section 2), followed by the cross-check of paper 1's culling of EDRs (section 3), followed by discussions of new measurements of the seventh sieve (section 4). Section 5 treats the impasse of magnetized EDRs. The implementation of sieves of paper 1 is treated in section 6, followed by what one could conclude if all sieves were satisfied (section 7) versus what one should conclude when an event fails a proxy test (section 8). The status of the dialogue about identifying the EDR of CMR concludes in section 9.

2. Seventh Sieve for the EDR: Demagnetization of Thermal Electrons

[6] With our entry into this dialogue there is a new, seventh and independent criterion for the list and a new pragmatic screen: the necessity that the thermal electrons be demagnetized in the EDR; it is clearly independent of those 6 tests on the electromagnetic field used to find the 117 events reported in paper 1. We propose to use this new test as a "cross-check" on the winnowing process. If the 6 screen, winnowing process of paper 1 has rooted out all rogue current layers, leaving only actual EDRs of CMR, this new test should affirm this situation. Alternatively, since this new screen was not used to select the candidate layers of paper 1, its verdict cannot be foreseen. Thus the hypothesis that the screens of paper 1 can find EDRs of CMR is, by virtue of our contribution to this dialogue, a falsifiable hypothesis.

[7] As our initial contribution to this dialogue we formulate a proxy test for the demagnetization of the thermal electrons in these layers. Such a test is structurally different from those in paper 1, since it inventories the kinetic situation of the thermal plasma rather than the electromagnetic field and its gradients. The criterion that thermal electrons must become demagnetized in the EDR summarizes a necessary criterion of the current theoretical view of the EDR of CMR. In the absence of binary collisions, steady CMR needs to support the conserved reconnection electric field at the stagnation point in the flow, where the unipolar field cannot. If the description of reconnection is restricted to two dimensions, the arguments are overwhelmingly in favor of a strong role being played by the electron pressure tensor at the stagnation point, which must be deformed from the traditional cylindrical symmetry of a strongly magnetized plasma. Dating from *Vasyliunas* [1975], it has been foreseen that the electron pressure tensor there should be agyrotropic (i.e., not gyrotropic or nongyrotropic), reflective of the demagnetization of the thermal electrons. PIC simulations in two dimensions have provided strong support for these theoretical concepts; although 3-D simulations are still in their infancy, they too have presented supporting evidence [*Yin et al.*, 2008] that demagnetization via the agyrotropy of the electron pressure tensor is still prominent in the EDR.

[8] Theoretically plasma kinetic regimes are often ordered by the guiding center expansion parameter $\delta = \rho/L$ where ρ and L are the gyroradius and scale lengths of variation, respectively. The regime of demagnetization should be defined by its contrast with the adiabatic, guiding center, magnetized regime where, for electrons

$$\delta = \frac{\rho_e}{L} \ll 1 \qquad (1)$$

is the expansion parameter size when the particle orbits are well described by guiding center (GC) theory. Such a theory predicts the motion of the guiding center as a power series in δ [*Northup*, 1963]. Accordingly, the regime of demagnetization (where simple first-order guiding centers drifts do not replicate the orbital behavior) occurs in a regime where this ratio is substantially of order unity:

$$\delta \simeq 1. \qquad (2)$$

This should be clear by thinking about integrating the full equations of motion in a spatially varying force field with the scale of the forces the same order as the incident thermal gyroradius.

[9] Moreover, the corrections to the gyrotropic guiding center pressure tensor scale like δ^2 [*Hazeltine and Waelbroeck*, 1998]. Agyrotropy then also scales like δ^2. Significant agyrotropy will not ensue unless δ comes close to, or exceeds unity. Accordingly δ^{-2} is a relative, but quantitative measure of how magnetized (guiding center ordered and gyrotropic) is the regime traversed. The yardstick is relative to unity, which most would agree is a significantly demagnetized regime that characterizes the EDR. This regime has also been confirmed with PIC simulations of the reconnection layer (J. D. Scudder and W. Daughton, Dimensionless, rare, single spacecraft, scalar observable properties of the electron diffusion region of collisionless magnetic reconnection, submitted to *Physics of Plasmas*, 2008; hereinafter referred to as Scudder and Daughton, submitted manuscript, 2008a) where pictures of this ratio within the separatrix have been exhibited. It should be noted that even the property of electron agyrotropy is not sufficient by itself to identify the EDR, since Vlasov equilibria with agyrotropy exist that are not sites of reconnection (e.g., the Harris sheet with background or the generalizations by *Mahajan and Hazeltine* [2000] and *Matsui and Daughton* [2008]). However, these and other solutions like them occur at thin electron scale current sheets that are highly susceptible to tearing when perturbed.

3. Cross-Check of Paper 1's Culling of EDRs

[10] The context plasma parameters presented in paper 1 that attended the 117 events can now be used (as published) to estimate the state of demagnetization of the "EDRs" identified in paper 1. The "EDR" study suggested confirmation of the electron skin depth scale of the reported layers (paper 1, paragraph 1); in this circumstance the electron

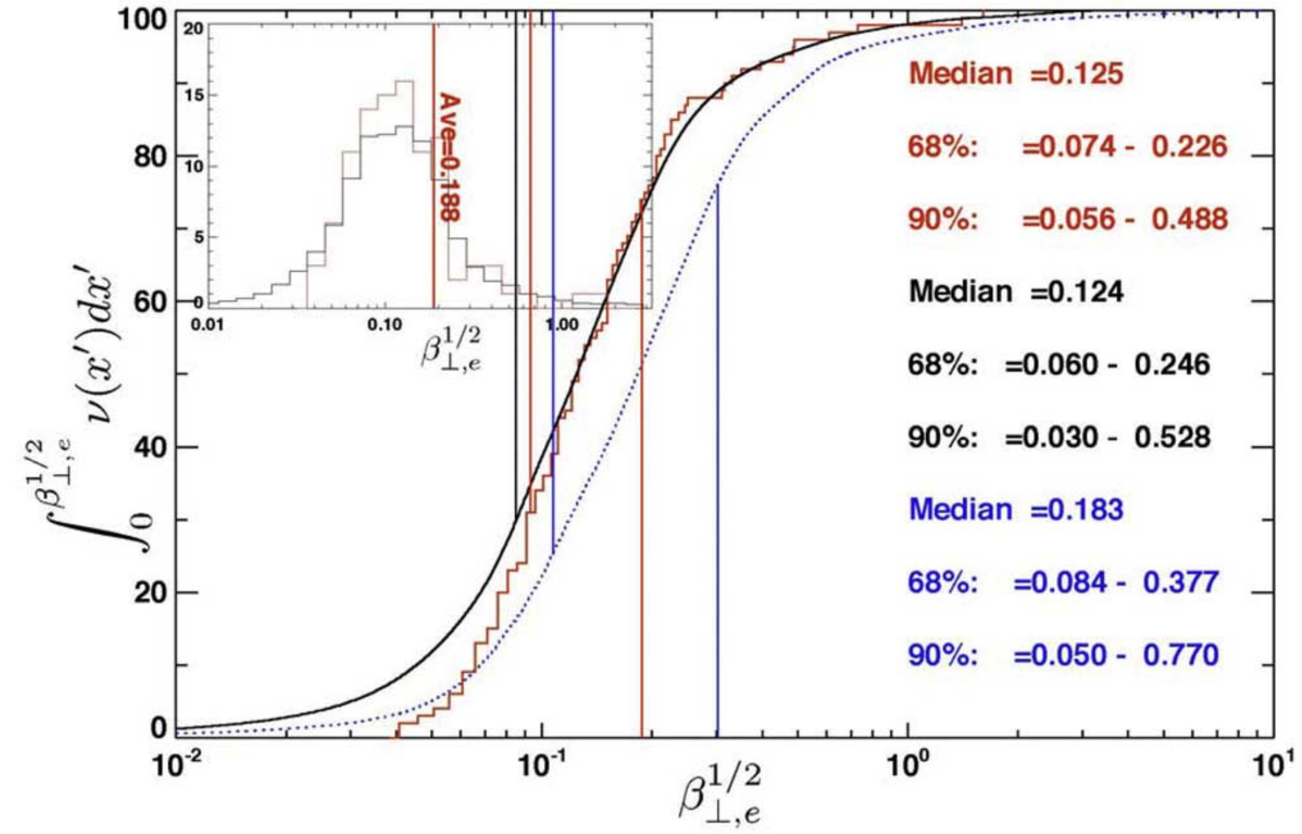

Figure 1. The cumulative distribution (red, black) of $\beta_{\perp e}{}^{1/2}$ that are the closest available measurements to each "EDR," as contrasted with the cumulative distribution (blue) of $\beta_e{}^{1/2}$ (T = 200 eV) used in the "EDR" study.

adiabatic ratio is exactly determined by the perpendicular electron beta:

$$\delta \equiv \frac{\rho_e}{L} \simeq \frac{\rho_e}{d_e} \equiv \beta_{\perp e}^{1/2}. \qquad (3)$$

Figure 14 in paper 1 shows the distribution of inferred (but not measured) electron β_e formed from densities inferred from spacecraft potential measurements and a time independent assignment of $T_e\ (t) \equiv 200\ eV$ for all events covering a 3 year period. In paper 1 β_e is strongly peaked in a logarithmic histogram at 0.1 (with 3 buckets per decade), which implies a modal value for $\delta^{-2} \simeq \beta_e^{-1} \simeq 10$. The most frequently occurring situation (using only data published in paper 1) is that the 117 layers are 10 times more magnetized than expected in the actual EDR of CMR. The average value of these data (see Figure 4) imply $\langle \delta^{-2} \rangle$ is even higher (more magnetized) than this conservative estimate.

4. New Observations of the Seventh Sieve

[11] Our second contribution to the dialogue is to introduce the appropriate local values of the perpendicular electron beta measured closest (<2.3 s) to each "EDR" event (see Appendix A for data pedigrees) determined by the Hydra hot plasma detector on Polar [*Scudder et al.*, 1995]. This avoids the unnecessary assumption of constant temperature made in paper 1. At the same time a locally measured electron density and thermal anisotropy (from the full diagonalization of the pressure tensor) that is closest in time to each "EDR" event is used from the Hydra data on the same spacecraft: Polar. On average the actual plasma electron temperature/anisotropy properties made the measured $\beta_{\perp,e}$ nearly 50% lower than its estimated value in the "EDR" study. This is reflected in Figure 1 for $\beta_{\perp,e}^{1/2}$, using cumulative distributions for the closest measurement to each of the 100 events. With a mean of 0.188 that is very nearly $\sqrt{0.1/3}$, these measurements make the modal magnetization of the "EDR" events now 30 times the expected value of order unity appropriate for the EDR of CMR. Thus the "EDRs" as a set are seen to be even more magnetized, as we incorporate a better local plasma measurements (including anisotropy) into the evaluation.

[12] In an attempt to be very careful, we were aware that the happenstance of $\delta \simeq \beta_{\perp e}^{1/2}$ presupposes the accuracy of the $L \simeq d_e$ (stated in the abstract of paper 1), which was not actually measured. If there were sizable variability in this assessment, it could modify our evaluation of degree of magnetization.

[13] Our third contribution to this dialogue has been to recognize another relationship of Finite Larmor Radius (FLR) ordering [*Hazeltine and Waelbroeck*, 1998] that connects our desired adiabatic expansion parameter δ and the ratio of the perpendicular electric to magnetic force

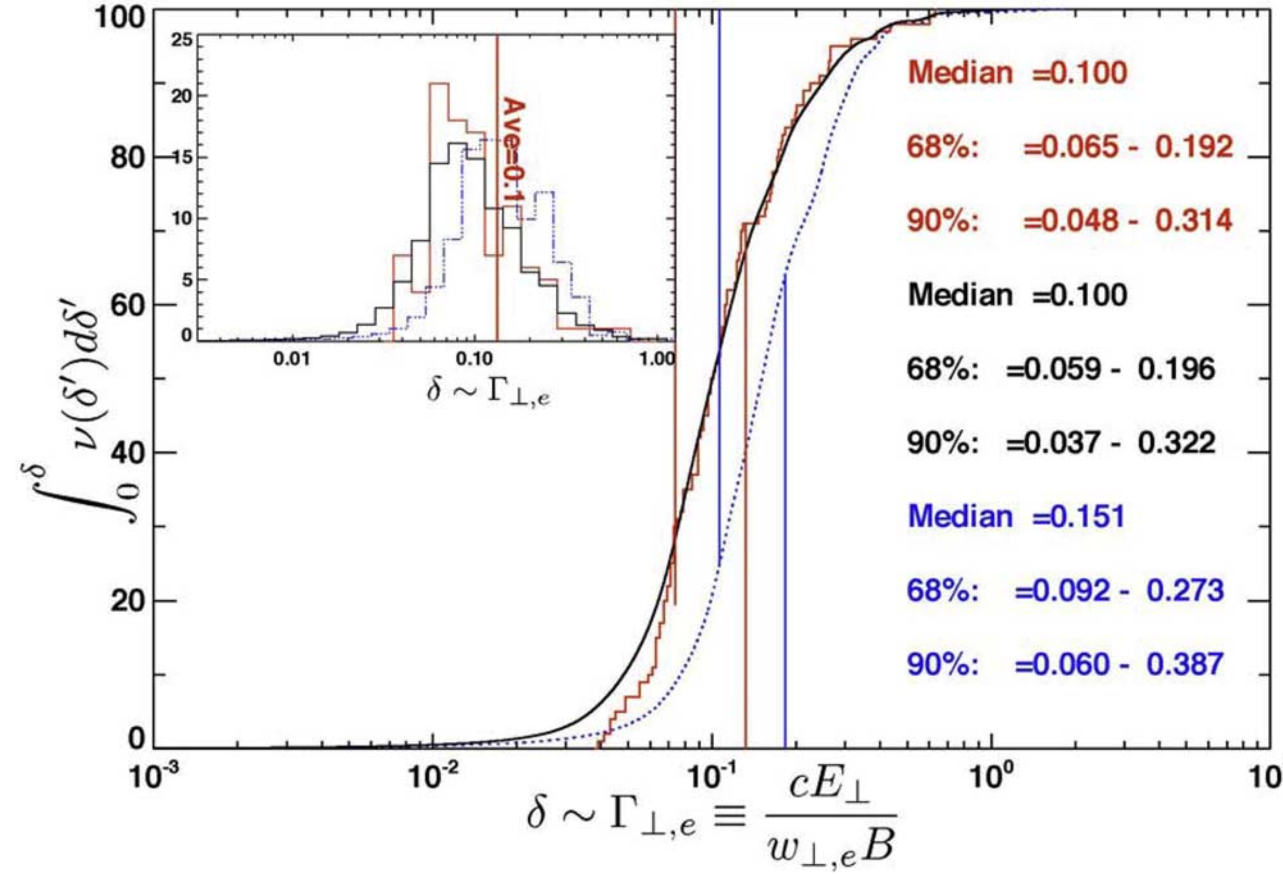

Figure 2. Cumulative distribution of the Lorentz ratio for the "EDR" events. This ratio also scales like the electron adiabatic expansion ratio δ: $\Gamma_\perp$ [cf. *Hazeltine and Waelbroeck*, 1998]. The blue curve is for the extreme aliasing assumption discussed later in the paper.

experienced by a thermal speed electron in the electron fluid's rest frame:

$$\delta \equiv \frac{c|\mathbf{E}_\perp + \mathbf{U}_e \times \mathbf{B}/c|}{w_{\perp e}B} \simeq \frac{c|\mathbf{E}_\perp|}{w_{\perp e}B} \equiv \Gamma_{\perp,e}, \tag{4}$$

where the approximation in equation (4) is valid for very strong $E_\perp$ as in the present study and where the thermal speed used in (4) is determined by the perpendicular temperature of the electrons: $w_{\perp e} \equiv \sqrt{\frac{2kT_{\perp e}}{m}}$. This ratio had figured prominently in earlier work where this ratio was termed the Lorentz ratio and labeled $\Gamma_\perp$ [*Scudder and Mozer*, 2005] and is discussed extensively by J. D. Scudder and W. S. Daughton (The unusually large dimensionless strength of the electric field in the electron diffusion region, the cause of electron demagnetization in collisonless magnetic reconnection) (hereinafter referred to as Scudder and Daughton, submitted manuscript, 2008b). We have determined this adiabatic ratio directly from observations, using the best local "EDR" parameters from the Polar electric field [*Harvey et al.*, 1995; F. S. Mozer, private communication, 2007], the Polar magnetic field [*Russell et al.*, 1995] and the Polar plasma [*Scudder et al.*, 1995] instruments for all events (100 of the 117) when all instruments were operational.

[14] The results in terms of cumulative and ordinary histograms are recorded in Figure 2. By all statistical measures (mode, mean, average) δ is small with median 0.1 and average 0.12. From a guiding center perspective the "EDR" locales would be considered magnetized. As a further check on this technique, we have used it in reverse to determine the spatial scale length at the "EDR" layers. The average spatial scale found in this way is 80% larger than the electron skin depth upper bound suggested in the abstract of paper 1. The premise that "EDR" layers approach electron skin depth scales is thus approximately true. However, not every electron skin depth layer is an EDR. As shown above in equation (1), the possibility for demagnetization in such layers requires $\beta_{\perp,e} \geq 1$. Because the "EDR" events occur in low beta with these scales, they cannot be demagnetized. Figure 3 illustrates a map of Γ_e near the diffusion region of a PIC code to illustrate its exceeding unity in the separator EDR region (Scudder and Daughton, submitted manuscript, 2008).

[15] Since δ^{-2} is the relative measure of magnetization (from the pressure tensor scaling), we have assembled the cumulative and frequency histograms of this directly observed quantity using the approximation of equation (4). Using the mean (median) the "EDR" events are 135 (99) times more magnetized than theoretically expected for the EDR of CMR. The ranges of the data [29.3–231]([13.75–489]) at ±68% (±90%) about the median indicated on Figure 4 leave little doubt that the "EDR" events of paper 1 are strongly magnetized in spite of having passed the six

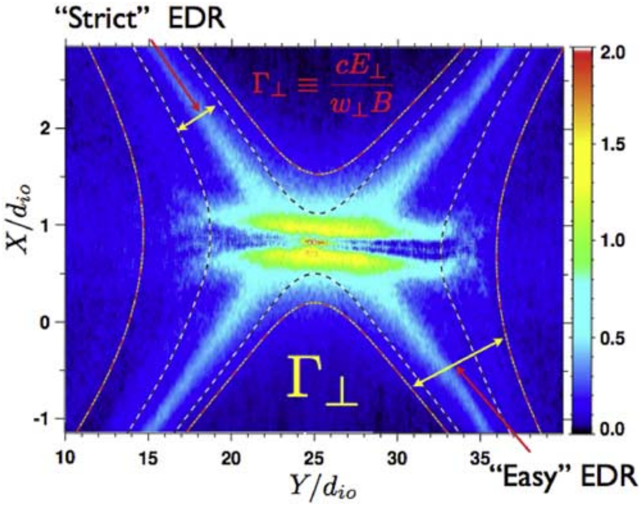

Figure 3. Lorentz ratio $\Gamma_\perp \simeq \delta_e$ (the adiabatic ratio) adapted from Scudder and Daughton (submitted manuscript, 2008a) from PIC simulation of the EDR in antiparallel geometry using a mass ratio of M/m = 100. The EDR is outlined at two different levels of departure from nonidealness, (1) easy and (2) strict, depending on how low the electron agyrotropy gets below the peak values at the separator. The central point is the large values of the Lorentz ratio that occur in the inner EDR. Of particular importance is the intensities in excess of unity and even above 2 right near the separator. Also clear in this view is the ridge of enhanced but lower Lorentz ratio out along the separatrices where values as high as 0.5 occur even $10d_{io}$ downstream of the separator along the separatrices. The dashed black and white lines are four bounding magnetic field lines of the EDR. The bounding red and yellow dashed lines illustrate four other magnetic field lines that would provide the border to the EDR in the "easy" definition.

screens of paper 1. In this way we document by a variety of statistics that with high confidence the "EDR" are conservatively 100 times more magnetized than expected for the EDR of CMR.

5. Impasse: Magnetized "EDRs"

[16] At this point the dialogue turns introspective. Logically, a magnetized current layer identified as the EDR of CMR is an oxymoron. Above the best and most proximate measurements have been brought together to test the sifting capability of the six screens of paper 1 for finding the EDR. From the cumulative distribution in Figure 4 it should be clear that barely one of the 100 events has a magnetic disorganization comparable to unity that is expected in the EDR! If the measurements and reasoning about demagnetization are well formulated, there must be some serious deficiency/inadequacy in the six screens for isolating current layers that are likely EDRs from other layers.

6. Implementation of the Sieves of Paper 1

[17] We now dialogue about the six criteria/tests used to find the "EDRs" in paper 1. The "EDR" study used the following "operational definition of the electron diffusion region as any region that satisfied the following six conditions: (1) nonzero $E_\|$; (2) change in magnetic topology and $\mathbf{E} \times \mathbf{B}$ flows on either side; (3) 'disruptive' $E_\perp \gg E_{\mathrm{Recon}}$; (4) large $\mathbf{J} \cdot \mathbf{E} \gg \mathbf{0}$; (5) a scale $L \simeq d_e$; and (6) acceleration of electron beams" (reordered from paper 1, paragraphs 14–19).

[18] We use Table 1 to summarize in turn the content, implementation, and our evaluation of the suitability of each criterion and proxy test used in paper 1. Paper 1's proposed proxy test of the science criterion in the second column is summarized in the fourth column. The second and fourth columns reflect an experimentalist's pragmatism, formulating a workable test of observables argued to be a necessary antecedent for meeting the original science criteria. The logical train is long between the criterion (which most would agree on, but see below) and a necessary precondition for successfully testing for the criterion. For a successful screen the pragmatic test must at least be necessary and have an objective standard for success. Certainly, first drafts of such proxy tests need to be studied for their compatibility with the criterion being replaced. We view this ongoing dialogue as a forum to vet, model, test and, where necessary, improve the proxy tests, or even find new ones.

[19] 1. Perhaps the clearest logical connection between a science criterion and its proxy necessary test in paper 1 is Criterion I, where the experimentalist avoids attempting to check $\mathbf{B} \times \nabla \times E_\| \hat{\mathbf{b}} \neq 0$ by checking on $E_\|$'s existence. Because $E_\|$ must logically be nonvanishing for it possibly to have a curl, the proposed proxy test is indicated in the fifth column of Table 1 as a reasonable substitution for the first criterion. Although seemingly clear-cut, the nonzero curl condition is part of a requirement that a surface integral over this quantity be nonvanishing. The parallel electric field can go through zero in very complicated ways and still cause this integral to be nonvanishing. The plausibility of this test hinges on what the experimentalist means when indicating that $E_\| \neq 0$ for the "EDR" event. This could mean it is zero nowhere in the interval of the event. The spirit of the test is that the data contradict $E_\| \equiv 0$ throughout the event. Paper 1 does not say what conditions on $E_\|$ were checked to ensure compliance with this test. Clearly, such a test is not sufficient, but it represents an intermediate necessary threshold that an event must surmount to possibly have a chance of success with Criterion 1.

[20] 2. Topology change is a necessary property of CMR and is the focus of Criterion II. Historically this has been addressed by finding normal components of **B** or later Walen tests through the layer [e.g., *Sonnerup and Scheible*, 1998]. The "EDR" study suggested a new way to test for this necessary change of magnetic topology by detecting flow changes (reversals) in the transverse components of the $\mathbf{E} \times \mathbf{B}$ velocity as a suitable proxy for this change of topology. This approach was justified in a companion study by writing [*Mozer et al.*, 2005, L24102–L24104, paragraph 21] (hereafter paper 1a),

> "…(I)n the standard picture of reconnection the electron diffusion region is a boundary across which the tangential $\mathbf{E} \times \mathbf{B}/B^2$ flow changes because the fields on the two sides are decoupled."

However, this rationale ignores the fact that tangential discontinuities separate two magnetically uncoupled regions and can (and often do) have arbitrary tangential flows on

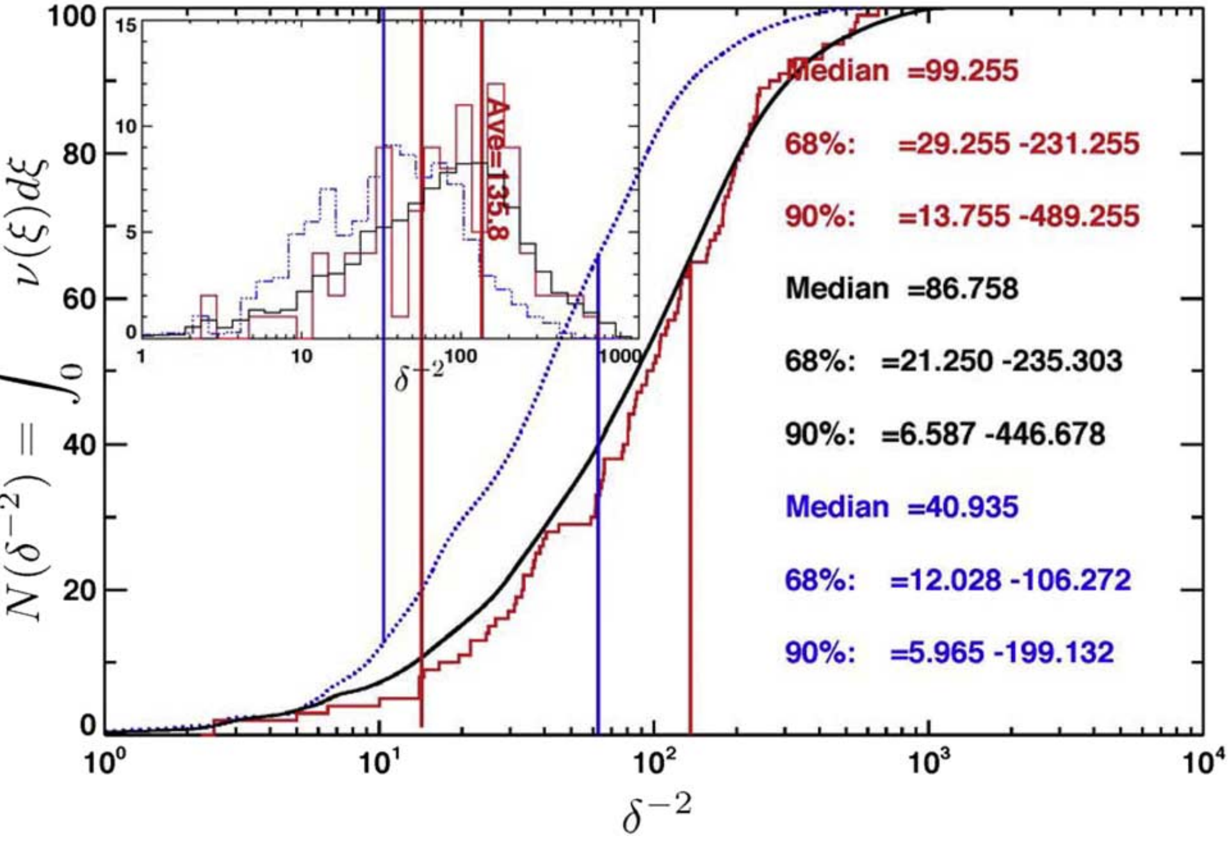

Figure 4. The horizontal axis indexes degree of magnetization of thermal electrons in "EDR" events in paper 1 relative to the expected value of unity in the EDR of CMR. The "EDR" events are 99 (135) times more magnetized than expected using median (average) values for the yardstick. The modal values are 13–15 times more magnetized than expected in the EDR.

either side [*Burlaga*, 1995], without having anything to do with being the EDR or thus CMR.

[21] In paragraph 22 of the same paper the authors expand on the importance of tangential flow reversals:

> "…However, in the central third of the plot, while the two spacecraft were on opposite sides of the boundary, the tangential y and z components of the flow were in opposite directions at the two spacecraft. This topological difference was constant for a period of at least several seconds."

On the basis of an analysis of flow patterns in simulations and theory (J. D. Scudder, Disproof of proposed necessary test for change of magnetic topology in collisionless magnetic reconnection, submitted to *Physics of Plasmas*, 2008) we have indicated in the fifth column that this test is actually not a necessary corollary of CMR. The proposed "EDR" test for the Criterion II has been shown to be only necessary for the guide field geometry CMR, and would fail all antiparallel geometries. In this example a well-inten-

Table 1. "EDR" Criteria Used to Identify Events as the EDR of CMR[a]

	Criterion	CMR Req'd?	Proposed Test	Valid?	On Polar?	Not CMR Example	Comments
I	$\nabla \times E_{\|}\hat{\mathbf{b}} \neq 0$	Y	$E_{\|} \neq 0$	Y	Y	$\hat{\mathbf{b}} \cdot \nabla P_e \neq 0$	No Cluster Check
II	B Topology Δ	Y	$\mathbf{E} \times \mathbf{B} \cdot (\mathrm{I} \cdot \hat{n}\hat{n})_j$ Δ sign	N	N[b]	TDs with Flow Shear	–
III	$E_\perp$ "Disruptive"	Y	$E_\perp \gg E_{Recon}$	N[c]	Y	Super-Alfvenic Flow Solar Wind	–
IV	Large, Positive EM → Particles	Y	$\mathbf{J} \cdot \mathbf{E} \gg 0$	N	Y	Shocks, RDs	Requires $\mathbf{J} \cdot (\mathbf{E} + \mathbf{V}_{rel} \times \mathbf{B}) \gg 0$ No $\mathbf{V}_{rel}$ used
V	$L_{EDR} \simeq d_e$	Y	$\bar{V}_{rel,j}\, \Delta t_j \simeq d_e$	Y	N	General Current Penetration Scale	Cluster Check
VI	Particles Rec'd EM Power	Y	e^-(500 eV) Beams $\mu = \pm 1$	N	N	Skew Common $f_e(\mathbf{v})$	No Specified Exit Channel

[a] The first column is the general sense of the criteria. The second column specifies whether it is a CMR requirement. The third column is the proposed test in symbols. The fourth column answers the question whether the proposed test is a necessary corollary to the respective criterion; that is, if it fails this test the criterion is not met. The fifth column evaluates whether or not the proposed test was done for the Polar "EDRs." The sixth column gives an example or class of examples that coexist with EDRs of CMR that satisfy the criterion. The final column is for explanatory comments or clarification.

[b] No normals.

[c] See Discussion.

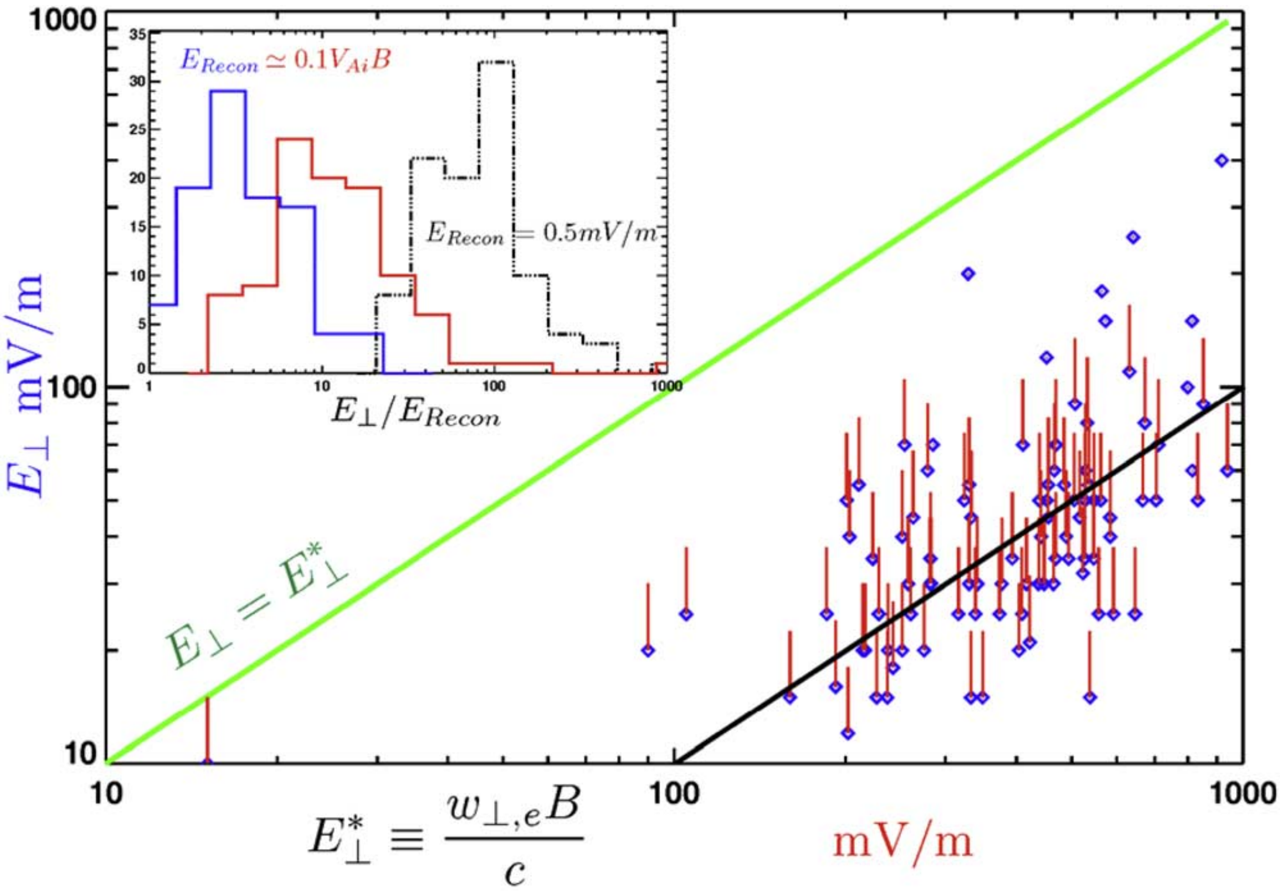

Figure 5. Horizontal axis is the limiting disruptive field in terms of local perpendicular electron thermal speed and B. Vertical axis is $E_\perp$. Data at "EDRs" of paper 1 are indicated by blue diamonds; red flag extensions are possible augmentations of observed $E_\perp$ to account for possible aliasing. Those without red flags caused burst modes on EFI and have already had their peak electric field strength incorporated in the blue diamond plotted. Inset (red, blue) shows the distribution of the observed $E_\perp$ in units of two different estimates for the local reconnection electric field based on inflow rates of 0.1 the asymptotic Alfven speed at local position of observer (red histogram) and inferred by the nearby maxima of this quantity (blue histogram) within ±30 s of event. Black dashed curve is the distribution of the perpendicular electric fields in units of 0.5 mV/m. Note that the electric fields of the "EDR" types are not substantially different than the local reconnection electric field, appearing to contest the disruptive label placed on them in paper 1.

tioned but nonetheless heuristic test of a widely subscribed criterion cannot help to screen for EDRs by excluding antiparallel geometries of CMR. The test is thus not logically a necessary precondition to a CMR layer of unknown geometry. Because a true EDR with antiparallel geometry would fail the proposed test in the "EDR" study, the proposed test of Criterion II cannot be a necessary screening test that "EDRs" are reconnection layers.

[22] A secondary matter is that the test described was not objectively performed on Polar "EDR" intervals (sixth column). To perform the indicated test the local current sheet normal must be determined to give meaning to "transverse" components called out in the test. None were reported as having been used for the "EDR" events. By presenting the data in GSE coordinates, the impression was given that the normal to the layers were assumed to be in the radial direction. While all reconnection layers must have flow reversals along the normal, these are small and appear not to be those intended by paper 1 as clarified by their paraphrase of the criterion in the companion study of paper 1a (paragraph 21).

[23] 3. Criterion III of paper 1 introduces a new, necessary requirement for detection of the EDR of CMR. The suggested necessary criterion introduces the concept that "...$E_\perp$ must be large...for the electron diffusion region to exert an important influence on reconnection" (paper 1, paragraph 16). We will refer to this criterion as the suggestion that $E_\perp$ is "disruptive." The companion study (paper 1a) suggested this condition should be enforced "...(in order that diffusion be effective)..." (paragraph 5). The proffered proxy test was that $E_\perp$ exceed a threshold (fourth column) of the canonical reconnection electric field associated with inflows of 0.1 of the asymptotic Alfven speed, namely,

$$E_\perp \gg E^\infty_{\mathrm{Recon}} \simeq 0.1 V_{\mathrm{Ai}\infty} B_\infty, \tag{5}$$

This test appears to have been enforced by assuming the right-hand side of (5) was 0.5 mV/m for all events (see below in Figure 5).

[24] As published the condition and test threshold of equation (5) hardly appear defensible, precisely because there is no physical rationale for either rooted in properties or consequences peculiar to the EDR. For example, how does $E_\perp$ exceeding the relatively weak reconnection MHD field strength impact "diffusion"? This is an example of a totally unvetted proxy test. Further, since the threshold for the inequality is so small (whether taken as 0.5 mV/m or as the equivalent of $0.1V_{Ai\infty}$ in the local B) on the scale of MHD electric fields, most any measurable electric field is a priori larger than it. Thus the test is satisfied by most observable electric fields and does not aggressively sift for compliance.

[25] We contribute to this dialogue an alternate proposal and physical rationale for deducing the size of $E_\perp$ to be influential/disruptive and permit departures from frozen flux in the EDR of CMR (Scudder and Daughton, submitted manuscript, 2008a). Strong perpendicular electric fields in narrow layers of order the electron gyroradius can play an important role in the demagnetization of the electrons [*Scudder and Mozer*, 2005]. As far as we presently understand, electron demagnetization is a necessary condition for the EDR to become a site where the frozen flux description is strongly relaxed, enabling the large-scale change of magnetic topology of CMR. (This regime is sometimes referred to as "diffusive" borrowing language from resistive MHD, in spite of the radical differences in CMR.) The proposed test as a proxy for this disruption (in paper 1) is not a valid restatement ("N," fifth column) of the demagnetization of the electrons that we suggest is the essential object of this "disruptiveness." We have derived two equivalent forms for the threshold condition for disruptiveness appropriate for demagnetization (Scudder, submitted manuscript, 2008a). The first has been tailored to compare with the inequality proposed in paper 1:

$$E_\perp(x)' > E_\perp^* \equiv 10\sqrt{\frac{M}{m}}\beta_{\perp e}^{1/2}(x)E_{\mathrm{Recon}}(x) \tag{6a}$$

Alternatively, this expression states that the excess electric drift in the electron bulk rest frame exceeds the electron thermal speed associated with the perpendicular temperature:

$$c\frac{E'_\perp(x)}{B(x)} \geq w_{\perp e}(x). \tag{6b}$$

Typically at the magnetopause $\beta_{\perp e} > 6 \times 10^{-6}$, so that the "demagnetizing" disruptive threshold $E_\perp^*$ of (6a) strongly exceeds that of the "EDR" study's threshold in (5), even when a locally varying value for the reconnection electric field is used. At the typical betas documented above $E_\perp^*/E_{\mathrm{Re}con} \simeq 94$, making the threshold for the desired disruption two orders of magnitude larger than the local conserved reconnection electric field. Conditions (6a) and (6b) represent an objective threshold for compliance and a size that is "unusual" relative to MHD electric fields; further, it is a way to foresee strong relaxation of the frozen flux behavior in the EDR. The condition of paper 1 includes our proposal as a subset; the corollary is that the paper 1 proxy has a threshold for compliance that is 100 times too small and is consequently rendered totally ineffective as a screen for good candidates for EDR.

[26] Figure 5 illustrates the results of testing for the demagnetization of thermal electrons in terms of the local electric and magnetic fields. The horizontal axis is the locally demagnetizing electric field $E_\perp^*$, while the vertical axis is the observed $E_\perp$. The location of "EDR" event fields is indicated by the blue diamonds. The red vertical flags reflect an error that might have led to an underestimate of the electric field strength whenever an EFI burst mode was not triggered by the "EDR" event. The green diagonal line is the suggested disruptive demagnetization threshold (Scudder, submitted manuscript, 2008a). Figure 5 demonstrates that even with caveats 99% of all "EDRs" are well below the green disruptive line of this threshold. The black diagonal line is drawn to guide the eye that the peak electric fields are about 0.1 of the local disruptive threshold. The inset histograms illustrate the properties of the "EDR" data against three variants of the proposed threshold of paper 1. The red histogram illustrates the distribution of $E_\perp(x)/E_{\mathrm{Recon}}(x)$, which tends to overestimate the desired ratio versus an asymptotic (and larger) motional electric field $E^\infty_{\mathrm{Recon}}$ away from the reconnection layer (Here we have distinguished between evaluating (5) with local Alfven speed and field strength, $E_{\mathrm{Recon}}(x)$, as opposed to estimating it at infinity $E^\infty_{\mathrm{Recon}}$, where the observer usually has not sampled.). The mode of the red distribution is 6–7. Using ±30 s about the event to find the maximum value of the reconnection electric field, we obtain the blue histogram, with mode of 2–3. The events normalized by a constant estimate of the reconnection electric field of 0.5 mV/m gives a modal value of 100. From this perspective the "EDR" electric fields are not significantly larger than the local (red), or even best estimate of the asymptotic reconnection (blue) electric fields. In this sense they are not unusual. It would appear that the compliance reported in paper 1 with its disruptive proxy test condition of paper 1 was based on the distribution in black in the inset, comparing the variety of $E_\perp$ with a constant reference of 0.5 mV/m.

[27] We conclude that this test, even as formulated in paper 1, was not performed in the proper dimensionless variables, since the compliance with the proposed test involved $E_\perp \gg E^\infty_{\mathrm{Re}con}$, which the red/blue inset histograms in Figure 5 show are only order unity removed from the best estimates of the asymptotic reconnection electric fields. We also conclude that these electric fields are not sufficiently large to cause significant demagnetization, being only 10% of the threshold required to demagnetize thermal electrons and interrupt the frozen flux description of the dynamics.

[28] Figure 5 and inset show that

$$E_\perp^* > E_\perp^{''EDR''} > E_{\mathrm{Re}con} \tag{7a}$$

and that

$$E_\perp^*(x) \simeq 10\left(E_\perp^{EDR}(x) \simeq 3E^\infty_{\mathrm{Re}con}\right) \tag{7b}$$

Criterion III has the intuition that the EDR rearranges things, is disruptive, but its ancillary test (Table 1) does not monitor the physical circumstances necessary to disrupt the frozen flux approximation. It did not have a suitable threshold to ferret out electric fields that can disrupt the magnetization of the thermal electrons. Conditions (6a) and (6b) should assure that the demagnetization of thermal electrons occurs. As our initial contribution to this dialogue has shown, the electrons at the "EDR" events are not demagnetized at all; Figure 5 restates this finding in terms of the electric field threshold. It is in this sense that the III test of paper 1 summarized in the fourth column of Table 1 does not propose a hurdle that is special for CMR.

[29] After the main results of this paper were completed and shared informally with the author of paper 1, a dialogue ensued about the possibility that the size of the peak electric fields used by us were systematically underestimated, especially those that had not already been updated by the procedure discussed in Appendix A of this paper. For events where EFI burst mode data were simultaneously acquired, factor of 2 increases in peak electric field strength were observed. These increases were incorporated from the beginning in our study (reflected in red or black histograms above) and were included in all decisions to this point in the paper. The remaining "EDR" events that did not trigger parallel burst mode coverage may or may not have had a bias toward being too low an estimate of the peak electric fields. We have taken that concern seriously and used the experience from those few events where EFI burst mode and 40 Hz data are both available to consider that the peak value of "EDRs" not already corrected, should be enhanced by 50% of their 40 Hz values. We also enhanced their errors to reflect their grossly enhanced uncertainty as 50% of the original DC electric field at 40 Hz. In this way the original magnitude and the posited enhanced magnitudes are within one sigma of the enhanced mean value. The red flags on the blue diamonds of Figure 5 reflect the range where the blue diamonds could move if they were underestimated in this systematic way. As is visually clear, this outside aliasing possibility has no substantive effect on our conclusions, precisely because the largest electric fields were already corrected (having already activated a burst mode capture: diamonds with no vertical flags) and, because of the order of magnitude mean departure (black curve in Figure 5) of these field strengths from being critical for demagnetizing disruption. For completeness, other graphs (after Figure 1) already presented in this discussion were upgraded to include cumulative smeared distributions (in blue) and properties using this "ultraconservative" view of the observations that folds in the three sigma variance possibilities as discussed in Appendix B. Readers may review these figures to assure themselves there is no gross revision implied to our findings that the "EDR" layers are heavily magnetized. This ultraconservative and very remote possibility brings one event (on 27 February 2001 at 0018:28) in the bottom left-hand corner of Figure 5 close to the kinetically disruptive proposal we have introduced, but still leaves 99 of the 100 events well removed from being demagnetized. At best this one event is a marginal "detection."

[30] 4. Criterion IV of paper 1 is certainly a property of CMR ("Y," third column), namely, that Joule electromagnetic energy made available by CMR must be positive. While the criterion is unassailable, the pragmatic test bears scrutiny (J. D. Scudder, Signatures of Joule modification of plasma at possible sites of magnetic reconnection, submitted to *Physics of Plasmas*, 2008). Poynting's theorem reads [*Jackson*, 1998, p. 259]

$$\frac{\partial u_{\mathbf{E\&M}}}{\partial t} + \nabla \cdot \mathbf{S} = -\mathbf{J} \cdot \mathbf{E},$$

where $\mathbf{S}$ is the Poynting flux, $u_{\mathrm{E\&M}}$ is the electromagnetic field's energy density and the rhs is minus the Joule work done by the fields on the particles.

[31] The Joule term represents a sink to the field energy density. If B $\gg$ E then the partial derivative is Galilean invariant, so the reduction of energy stored in the field only constrains the sum

$$\frac{\partial u_{\mathrm{E\&M}}}{\partial \mathrm{t}} \simeq -\nabla \cdot \mathbf{S} - \mathbf{J} \cdot \mathbf{E} \tag{8a}$$

Let $\mathbf{E}'$ be the electric field in a frame where $\nabla \cdot \mathbf{S}' = \mathbf{0}$, then the time rate of change in this frame of the electromagnetic field $\frac{\partial u'_{E\&M}}{\partial t}$ is given by $-\mathbf{J} \cdot \mathbf{E}'$. If a Galilean frame transformation existed that would transform away all $\mathbf{E}_\perp$, Poynting's theorem would take on the form

$$\frac{\partial u''_{\mathrm{E\&M}}}{\partial \mathrm{t}} = -J_\parallel E_\parallel \tag{8b}$$

since $S'' = 0$ in this frame. When processing data without the benefit of a deHoffmann-Teller transformation and theorem that a constant frame shift will remove all perpendicular electric fields, it is not clear what sign $\mathbf{J} \cdot \mathbf{E}$ in (8a) should have in the spacecraft frame, as the structure moves overhead, etc. Without a simultaneous characterization of the divergence of the Poynting flux in the observer's frame of reference, a negative left-hand side of (8a) does not imply an expected sign for the Joule term, as apparently was discovered in paper 1a where equation (8b) was used without justification. Moving to a coordinate system where the local field line is at rest will remove the perpendicular electric fields and Poynting flux; however, a given time series analyzed then requires in general a sequence of noninertial transformations that also affect the energy of the particles in this frame. In this way particles measured at the same energy on the spacecraft will not be at the same energy in such a sequence of special reference frames where the Poynting flux vanishes.

[32] Since the test proposed by the "EDR" study is not Galilean invariant, and was not proposed in any special frame (other than rotation to GSE) found by the study, the sign of $\mathbf{J} \cdot \mathbf{E}_{s/c}$ appears to us to be unconstrained until the unreferenced divergence of the Poynting flux is simultaneously discussed. The manuscript does not introduce any other frames for its reported electric fields other than that of the spacecraft and GSE. A related concern is the determination of $\mathbf{J}$. The measurement of the current density is not discussed in the "EDR" study of Polar events. Its approximate orientation is constrained by Ampere's jump conditions (assuming a locally planar sheet current [*Jackson*, 1998]):

$$\langle \mathbf{J} \rangle \simeq \hat{\mathbf{n}}_{12} \times (\mathbf{H}_2 - \mathbf{H}_1)/L.$$

where L is the current thickness and $\hat{\mathbf{n}}_{12}$ is the local current layer's normal pointing from region 1 to region 2. Since current densities are not measured on Polar and since normals were not determined for the Polar "EDR" events, the sense/size of the current density and the orientation of **J** for the Joule dissipation estimate is insecure. In contrast with the Cluster events discussed in paper 1a, no normal determinations are discussed for the Polar "EDRs" in paper 1. Thus, Ampere's jump condition could not have been used in a systematic inventory of the direction, or size of the currents. For these reasons we have entered an "N" in the column concerning site for test performance.

[33] While a proxy test in some form was probably performed assuming $\hat{\mathbf{n}} = \hat{x}_{GSE}$ on Polar "EDRs," it is not clear from paper 1 that the sieve used involved theoretically appropriate diagnostics, performed in the correct reference frame and using a quantitative threshold for compliance, including compensation for the divergence of the Poynting flux in equation (8a).

[34] 5. Criterion V involves the expected electron skin depth scale of the EDR [*Vasyliunas*, 1975] ("Y," third column). The "EDR" study used the time intervals of events and archival inventories of typical magnetopause speeds to infer a rough order of magnitude (ROM) scale of the structures. Quantitative work about spatial scales can only be had with some type of phase front analysis to determine the relative velocity of the observer $\mathbf{V}_{\rm rel}$ along the local structure's normal $\hat{\mathbf{n}}$ to permit an accurate, objective conversion of time duration to a spatial length:

$$L \simeq \mathbf{V}_{rel} \cdot \hat{\mathbf{n}} \Delta t.$$

Neither local normals nor relative velocities were reported in paper 1. Even so, such ROM estimates were thought accurate enough to confirm compliance with the theoretical model. Such ROMs are unable to support the precision of the upper bound summarized in paper 1's abstract: "…is of the order of the electron skin depth or less" (paper 1, paragraph 1). As is well known, the speed and orientation of the local magnetopause interface is highly variable. Paper 1 (e.g., paragraph 1) repeatedly emphasized the atypical character of these events. Paper 1a analyzed the Cluster analogous events as if they were surface waves. In view of their novelty, it is not clear whether a "typical" range of magnetopause speeds is suitable for this type of quantitative reasoning for estimating the relative speed $\mathbf{V}_{\rm rel} \cdot \hat{\mathbf{n}}$. Given such systematics, the likelihood seems small to us that the relative speed over the observer's head of peculiar events called "EDRs" should conform to the average, typical, or range of selected magnetopause traversals inventoried 20 years ago. About half of the events by our measurements exceed the electron skin depth hard upper limit of the study's abstract. (By measurement we mean all variables of a theoretical relation that determine the length have been quantitatively observed, no ROMs.) The skew above the electron skin depth of the scale length population determined an average scale length of the "EDRs" 80% higher than the upper bound stated in the "EDR" study's abstract. This situation contributes another average multiplicative enhancement of $(1.8)^2 = 3.24$ to the strongly magnetized picture we have developed earlier. This brings the typical "EDR" layer to some 96 times more magnetized than expected for the EDR of CMR, providing a back of the envelope estimate of the range for δ^{-2} illustrated in Figure 4.

[35] The "EDR" study did not discuss if any events were prescreened for time duration thresholds. As described, all events under consideration were essentially postulated to be of the electron skin depth scale, thus vacating any rejection of events that were too long or too short.

[36] The "N" in the sixth column notes that the scale lengths that were measured were performed on Cluster events and then argued to constrain Polar "EDR" events. This criterion and VI below were both argued to be "validated" for Polar "EDR" events using Cluster data of these "analogous" events. It should be clearly stated that these are not events observed on both spacecraft. These are distinctly different events. This assertion of certification of 117 Polar events collected over a 3 year period using properties of an isolated group of events on Cluster is problematical. This is especially clear given that the existence of $E_\parallel$ is so important for establishing the analogy of layer type (sieve I) and that Cluster EFW experiment could not measure this important "analogous" quantity.

[37] 6. The last screening for a necessary criterion and necessary proxy test advanced in the "EDR" study was (paper 1, paragraph 18)

> "…Accelerated electrons must be produced in the electron diffusion region. The electromagnetic energy conversion should produce accelerated electron beams."

This approach is a rather specific variant of the more widely subscribed view of CMR that the plasma should show some visible signs of having received the Joule electromagnetic energy density that condition IV indicated was being released, with adequate corrections for the loss or gain of Poynting flux in the frame where the energy exchange is being monitored. While the overall energetics requirement of Poynting's theorem are general, they are also unspecific. Regardless of the frame adopted, Poynting's theorem does not determine "how," or "which part" of the plasma will accept the Joule work done or extracted from it [*Jackson*, 1998]. Since paper 1 has suggested a necessary criterion in terms of a specific species benefitting from the Joule dissipation, its proxy test is inordinately specific, for it to remain a necessary condition. Further, the suggested necessary test further requires that all the energy headed for the electrons is necessarily required to be found in the form of electron beams on the distribution function. Had the electron's stored their energy in convection and not as beams, paper 1's test would be unfulfilled, but this would not have been a contradiction to Poynting's theorem. If all of the Joule power was carried off by accelerated ions with electrons garnering nothing, there is no contradiction with Poynting's theorem. Accordingly the overly narrow form of the proposed criterion and even the proxy test for it cannot be supported as necessary. As a criterion this condition of paper 1 needs to be reframed in terms of the total time rate of change of energy density of all species of the plasma in the frame where Poynting flux vanishes; it should be framed to demonstrate that this total time rate of change of plasma energy in such a frame shall necessarily be correlated with the Joule work done by the fields on the particles.

[38] The "EDR" study offered "certification" of this effect for all 117 Polar events using a small group of different,

but argued to be “analogous,” events only observed on Cluster (paper 1a). In this context a single set of Cluster data that was not intercepted by Polar are in compliance with a rule (of paper 1) made for them. Regardless of the evidence they provide, the Cluster event data cannot provide “proof” of compliance of the 117 Polar events as having electron beams and being energized by Joule dissipation. Since this test was never performed on Polar data, it could not constrain the events selected.

7. If All Sieves Proxy Tests Were Passed, What Can One Conclude?

[39] At their best, all the proposed tests of paper 1 and the seventh one proposed in this paper were presented as necessary preconditions for a related necessary criterion of CMR. Even when properly vetted as necessary, each proxy test is not equivalent to the original criterion; it is just necessary for it to have a chance of being fulfilled. Further, being only necessary, compliance with a test does not imply the overarching criterion is satisfied or not! The only inference is that the compliance with the original criterion has not been precluded by the data passing the associated proxy test. If the data met the proxy test, Table 1 highlights non-CMR sites where the proposed necessary test is known to be fulfilled.

[40] There are some who argue that finding $E_{\|} \neq 0$ at a current layer with a scale approaching the electron skin depth is tantamount to finding the EDR. This thesis is equivalent to suggesting that when these two necessary tests are satisfied, together they become sufficient(!). Neither condition helps the other convert their necessary test to become sufficient for their related criterion of CMR. Skin depth layers exist in the absence of CMR. Parallel electric fields exist in the absence of CMR. As an example, knowledge of the d_e gradient scale of a layer does not permit the logical determination that the collocated observation of $E_{\|} \neq 0$ enables one to prove that $\mathbf{B} \times \nabla \times E_{\|} \hat{\mathbf{b}} \neq 0$! Clearly low electron beta current layers in equilibrium can have pedestrian pressure gradient parallel electric fields and be in equilibrium with skin depth scales and not necessarily be the EDR of CMR. The other entries in Table 1 also speak to other physical layers in hot plasma that have the selected properties to gain compliance with tests for criteria without being CMR layers.

8. Should an Event Fail a Proxy Test, What Can One Conclude?

[41] The first level of concern when an event fails a proxy test, is the status of the proxy test.

[42] Has it been vetted in other contexts than the paper where it is being used? Is it known to be general? Has it been discussed or evaluated in simulations, for example.

[43] However, should an event fail a vetted, necessary proxy test for a vetted criterion for CMR, the event is rejectable as being the EDR of CMR. Thus the importance of the seventh sieve is that it represents a vetted necessary proxy test that the events of paper 1 did not pass at the 99% level of confidence.

[44] It should be noted that the seventh sieve’s importance in this way is not because of its content, per se, but that it is a vetted, falsifiable test of a vetted criterion of the EDR of CMR that is different from those that isolated the “EDR” events of paper 1. Being outside the filters that “found” the “EDRs,” but still necessary, gives any seventh sieve the capability to filter further, or comment on the class of events acquired by the first 6 sieves as they have been applied.

9. Status of the Dialogue About Identifying the EDR of CMR

[45] Finding the EDR of CMR theory is difficult. To date all the well-documented EDRs are accompanied by essentially zero magnetic field strengths at the current sheet [*Scudder et al.*, 2002; *Mozer et al.*, 2002]. This does not argue that guide reconnection does not occur; rather it argues that the EDR sleuthing is more difficult in that geometry. The recent survey (paper 1) of 117 “EDRs” implicitly contained an internal contradiction shown above; its published supporting data clearly imply that the thermal electrons were magnetized, in spite of being identified/labeled as the (demagnetized) EDR of CMR theory.

[46] In this dialogue we have critically reviewed the evidence and strengthened it on both sides of this puzzle: (1) the new data analysis presented here establishes with very little doubt that the layers are magnetized insofar as thermal electrons are concerned, and (2) the review of criteria and tests used to isolate “EDRs” have been shown to contain logical inconsistencies and ROMS that are not experimental constraints. With more appropriate, accurate plasma data and new analysis techniques we have demonstrated with measurements that the “EDR” regimes are 4–13.5 times more magnetized than implied by the data published in the “EDR” study, and a factor of 40–135 overall more magnetized than expected in the EDRs of CMR theory.

[47] We have reexamined the criteria used to find “EDR” layers with a careful eye to the proxy tests suggested to be logical precursors of the theoretical tenets that motivated them.

[48] Overview of Sieves: From this inventory, we can see from Table 1 that only the first of the six criteria was (1) a valid necessary criteria for the EDR of CMR, (2) with a valid proxy screen and (3) actually tested in a meaningful way on Polar candidate “EDRs.” Further, of the six proposed tests in paper 1, only 3 were actually performed on Polar data products. The two remaining tests performed on Polar events were (1) a physically unjustified criterion about the disruptiveness of $E_{\perp}$ and (2) a proxy test for magnetic topology change that was not necessary to the criterion.

[49] From a Venn diagram point of view Figure 6 (left) indicates solid black ellipses that enclose each group of events that complied with the numbered tests of the “EDR” study. Their intersection set (green) is the “EDR” group of Polar events identified in paper 1. With the logic that satisfying multiple conditions is more restrictive than complying with fewer, the “EDR” study suggested that the “EDR” events had a “special” pedigree and, that they were the long sought for EDR of CMR theory.

[50] In the first half of the paper we have shown that the “EDR” events are not in the demagnetized set (the red

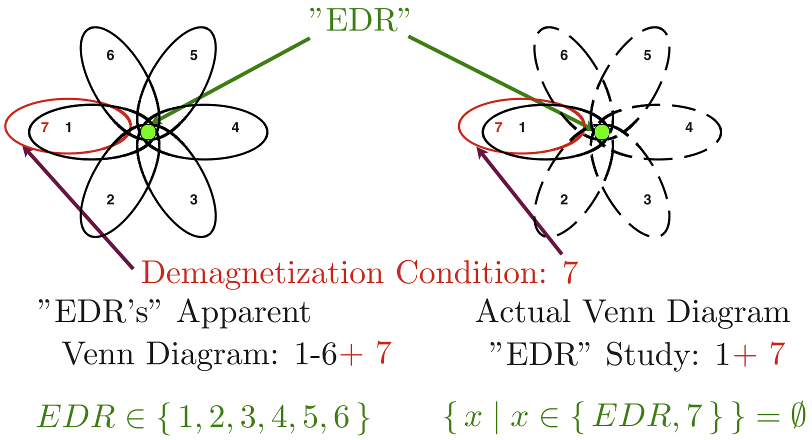

Figure 6. Conceptual Venn diagrams of the subgroups in the screening process implicit in paper 1. On the left is the circumstance with six necessary tests defining six (black) intersecting groups; all tests are suggested to be carried out with rigorous yes/no outcomes to define the green "EDR" intersection set. The argument of paper 1 is essentially that it is unlikely that events that pass all six tests are impostor EDRs. The first half of this paper has shown that essentially all of the "EDR" events are outside of the red subgroup of demagnetized events. Dashed ellipses (right) indicate those criteria that were essentially vacated, either by how they were performed or by being done on Cluster events that were argued to be "analogous" to the Polar ones in spite of no local $E_{\|}$ determination. The remaining solid black ellipse for detection of significant $E_{\|}$ is a screen that is necessary for CMR and was performed on Polar events. Unfortunately, the "EDR" events with $E_{\|}$ are not found to be sites where the thermal electrons are demagnetized (red ellipse), leaving the intersection set of one test with the demagnetized test empty at the 99% confidence level. As Table 1 demonstrates, the magnetized complement of $E_{\|} \neq 0$ events that can remain magnetized is substantial, including nearly all locales where there are magnetic field-aligned pressure gradients.

ellipse class) of events indicated in Figure 6. Now, after carefully reviewing each of the sifting operations performed around each of the criteria of the "EDR" study, we suggest that the net sifting operation looks more like the Venn diagram in Figure 6 (right), with most of the black ellipses having porous, perforated boundaries, indicated by their perimeters. They were either not "necessary," untested, not objectively tested, not tested with rigorous thresholds, or tested on "other" spacecraft events. In the presence of these systematics the multiplicity of tests need not enhance the rejection of rogue intervals, but gave a false sense of confidence that the winnowing process had selected the special layers. The only necessary screen tested on Polar data in the "EDR" study was that $E_{\|} \neq 0$. We have presented a new, necessary demagnetization screen for the EDR and tested the events of paper 1 for compliance. Thermal electron demagnetization is not realized in the events reported in the "EDR" study. In Figure 5, there is one event that might conceivably be consistent with both being in the nonvanishing $E_{\|}$ set and the demagnetizing set. We are thus looking at a 99% failure rate for the screens of paper 1 to select demagnetized layers as EDRs should be.

[51] Because the multiple criteria of paper 1 were not evaluated completely with all necessary precautions and with objective thresholds for success or failure, their multiplicity did not guard against chance compliance. Given these weaknesses in the enforcement of the proposed tests, and in light of the strongly reinforced experimental signatures of magnetization of the electrons at the "EDRs" presented in this paper, it appears inescapable to us that 99%, if not all, "EDR" layers are not regions of strong demagnetization, nor layers of intermediate demagnetization seen radiating from the separator in fully kinetic simulations [*Scudder and Daughton*, 2008; Scudder and Daughton, submitted manuscript, 2008a]. Accordingly, the "EDR" events fail the necessary and falsifiable test that they be regions where the thermal electrons are demagnetized.

[52] The dialogue needs to refine the observable properties of the EDR by including, and defending simultaneous, quantitatively enforced, stringent proxy tests that involve increasingly rare properties of the EDR of CMR such as the seventh sieve suggested here and direct detections of agyrotropy [*Scudder and Daughton*, 2008; *Scudder et al.*, 2007; Scudder and Daughton, submitted manuscript, 2008a].

Appendix A: Data Preparation and Pedigree

[53] "EDR" event times t_o to tenths of second resolution, peak perpendicular electric field strengths from the Polar EFI investigation [*Harvey et al.*, 1995], and magnetic field strengths from the Polar MFE investigation [*Russell et al.*, 1995] used for "EDR" identification were kindly supplied to us for this study (F. S. Mozer, private communication, 2007). The highest time resolution plasma data for computing $\beta_{\perp}e, w^{-1}_{\perp e}$ surrounding each event was available from the Polar Hydra instrument at a cadence of 2.3 s (but aliased over 1.15 s); these were interpolated to the "EDR" event time and errors propagated from counting statistics and interpolation. As the event times provided were coarser than

the 40 Hz electric field observations that were used to define events, and the "EDR" study used 8 Hz magnetic field observations, the 54 Hz magnetic field data from the MFE experiment (available through the Hydra telemetry), were averaged over $t_o \pm 0.025$ s to evaluate fairly the relevant B and variance for the required diagnostics of our analysis. Similarly, 54 Hz B averages and variances were determined for the separate locales where Hydra data were acquired. For calibration, MFE 8 Hz data available to Hydra were also interpolated to the event times for comparison with the EFI spread sheet of events with their electric and magnetic properties. These associations and validations were exchanged with the principal author of the "EDR" study, including the new plasma parameters. Several minor, clerical issues were cleared up by mutual agreement.

[54] The original study used the routinely available 40 Hz electric and 8 Hz magnetic field data to find events. When we proposed to perform the quantitative Lorentz test (using (4)) of this paper, the occasional availability of EFI simultaneous burst data was factored into the 40 Hz amplitude assessment of peak $E_\perp$ data provided to us (F. S. Mozer, private communication, 2007). Such estimates were assessed to be reproducible at the 10% level (F. S. Mozer, private communication, 2007). We first processed the data with these burst augmented indications of the perpendicular electric field and carried a 10% uncertainty for perpendicular electric field strengths in computed quantities.

[55] The Hydra moment analysis results have been discussed fairly extensively by *Scudder et al.* [2002] and *Scudder et al.* [1995]. There, recovery of the trace of the pressure tensor to 1% when in the 100 eV range has been documented. A similar precision occurs for the pressure tensor elements and is thus afforded for the anisotropy. Photoelectrons are routinely excluded by using the high time resolution floating potential from EFI. The multiple sensors of Hydra are routinely balanced assuming that gyrotropy is statistically pervasive. The absolute calibration of the sensors is monitored by showing that the return current voltage relationship [*Scudder et al.*, 2000] is maintained in a time independent way.

[56] Some composite quantities suffer from the mismatched time resolutions of their ingredients. Sometimes events are on the edge of precipitous decreases in the magnetic field strength. As we discuss in Appendix B, data quantities with significant error bars can yield misleading frequency histograms that are overly sharp and discontinuous depending on the binning. There we discuss our implementation of "spread" histograms that apportion a part of each event's $\pm 3\sigma$ range in X across buckets adjoining the mean's, while preserving the total unit area for each event that contributes to the spread histogram. In this way the spread of the estimates is folded into the spread histogram of occurrence. Most presentations will be in the form of cumulative histograms to assess what properties of the group of "EDRs" can be attributed with a given percentage of confidence, qualities that are often lost on histograms, especially when done in log space. Routinely the red histograms are the distributions of the mean values (without concern for their uncertainty), while the black histograms reflect the spread histogram of the same variables with their uncertainty for errors folded into the presentation. Because of turn on sequences and high voltage outages on the plasma instrument (caused by 6 monthly spin flips), it was only possible to refurbish the context plasma data to high time resolution for 100 of the original 117 events.

Appendix B

[57] At times event parameters have large error flags. For these events the average value is not a fair representation of the event. Accordingly, histograms are constructed of the 100 events in the following manner: A data point of variable X with one standard error σ occupies, with probability α = N exp $(-(X-\bar{X})^2/(2\sigma^2))$, an interval $X \pm 3\sigma$. If $X \pm 3\sigma$ extends to negative values, if X is intrinsically positive the interval is curtailed within $X \pm 3\sigma$ to reflect this circumstance, with attendant modification for N. Using a predetermined histogram bucket size the number of buckets k occupied by this spread out data point is found. The integral weight of α (x) found in each bucket is determined and N computed so that the weighted average of the center of occupied buckets is the reported mean value. In this way points with wide error bars contribute to a range of buckets. Histograms performed in this way are labeled as "smeared histograms," while traditional histograms that segregate only by mean value of X are referred to as "histograms" of "means." When distributions are plotted in log space this allocation of weights to bins is first performed in a linear histogram space, with its bucket limits subsequently deformed by the logarithmic presentation so as to always enforce equal total weight per "EDR" event.

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