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Substorm probabilities are best predicted from solar wind speed

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ABSTRACT

Most measures of magnetospheric activity – including auroral power (AP), magnetotail stretching, and ring current intensity – are best predicted by solar wind-magnetosphere coupling functions which approximate the frontside magnetopause merging rate. However radiation belt fluxes are best predicted by a simpler function, namely the solar wind speed, v. Since most theories of how these high energy electrons arise are associated with repeated rapid dipolarizations such as associated with substorms, this apparent discrepancy could be reconciled under the hypothesis that the frequency of substorms tracks v rather than the merging rate – despite the necessity of magnetotail flux loading prior to substorms. Here we investigate this conjecture about v and substorm probability. Specifically, a continuous list of substorm onsets compiled from SuperMAG covering January 1, 1997 through December 31, 2007 are studied. The continuity of SuperMAG data and near continuity of solar wind measurements minimize selection bias. In fact v is a much better predictor of onset probability than is the overall merging rate, with substorm odds rising sharply with v. Some loading by merging is necessary, and frontside merging does increase substorm probability, but nearly as strongly as does v taken alone. Likewise, the effects of dynamic pressure, p, are smaller than simply v taken by itself. Changes in the solar wind matter, albeit modestly. For a given level of v (or B_z), a change in v (or B_z) will increase the odds of a substorm for at least 2 h following the change. A decrease in driving elevates substorm probabilities to a greater extent than does an increase, partially supporting external triggering. Yet current v is the best single predictor of subsequently observing a substorm. These results explain why geomagnetically quiet years and active years are better characterized by low or high v (respectively) than by the distribution of merging estimators. It appears that the flow of energy through the magnetosphere is determined by frontside merging, but the burstiness of energy dissipation depends primarily on v.

1. Introduction

Perhaps the single clearest conclusion from the last four or five decades of magnetospheric theory and observational findings is that merging between the frontside magnetosphere and the IMF drives much of the dynamics. Thus most magnetospheric phenomena, including auroral power (AP) and ring current intensity are best predicted by using some estimator of the frontside magnetopause merging rate. Suitable ones include vBs, $d\Phi_{MP}/dt$, or the Sonnerup–Kan–Lee formula (Burton et al., 1975; Newell et al., 2007; Sonnerup, 1974; Kan and Lee, 1979). Most measures of geomagnetic activity, including indices such as *Kp* and *SME* (generalized *AE*) and *Dst* are also best predicted with coupling functions that serve as proxies for frontside merging (although sometimes considered conceptually different, vBs is surprisingly similar to the Sonnerup formulation for frontside merging, cf. Newell et al. (2007) or Wygant et al. (1983)).

Yet high energy particles, and in particular radiation belt electrons, turn out to be better predicted by using just v (Paulikas and Blake, 1979). Of course a large number of coupling functions have been proposed in magnetospheric physics by one author or another; however the findings of Paulikas and Blake (1979) have held up for the radiation belt, confirming this seemingly anomalous behavior (Reeves et al., 2011, 2013a, 2013b). Theoretical work and modeling efforts have generally supported the idea that these radiation belt electrons arise from the high energy tail of the general magnetotail plasma population after exposure to repeated dipolarizations, each of which provides a further boost to particle energy. Indeed, Baker and Kanekal (2008) have argued that radiation belt formation is impossible without substorm generated seed electrons, thus creating a direct link between substorms and radiation belt creation.

Here we explore what appears to us to be the simplest possible reconciliation of the discrepant solar wind responses: the

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frequency of substorms and dipolarizations depends primarily on v. Several corollaries promptly follow. For example, since AP (and ring current intensity, and so forth) mostly track frontside merging, substorms modulate the granularity of energy release, while having little if any effect on the total AP dissipated over time. Although perhaps puzzling at first, inasmuch as AP rises dramatically during a substorm, it must be realized that a substorm does not create any energy in the magnetotail, but merely determines whether that energy is being released smoothly or in bursts.

However if a phenomena depends not upon the actual amount of magnetic energy loaded into the magnetotail but rather largely upon frequency of dipolarizations, then for that phenomenon the primary coupling function would be just v. The creation of a relativistic electrons populating the radiation belt is just such a phenomenon.

The proximate cause of substorm onset has been one of the longer running debates in magnetospheric physics. The results presented here will not resolve the specific immediate instability triggering onset. In fact we are not investigating the immediate trigger or the fine scale timing of predicting substorms. The more modest goal is rather to ascertain the solar wind conditions conducive to higher or lower probability of substorm onset over the course of tens of minutes to a few hours, using a large and unbiased dataset. The best way to avoid hidden biases is to use data with continuous coverage, over many years, traditionally difficult when studying substorms. However, this is today possible because the global coverage and temporal continuity of the data sources contributing to the SuperMAG collaboration permit identifying substorms over many years without gaps.

The specific hypothesis that v by itself – above and beyond its role in driving merging – is a determining factor in the likelihood of substorm onset appears relatively unexplored. Partly this is because the frontside merging rate has proved so important in both theoretical and observational studies of magnetospheric behavior generally. Early attempts (Crooker et al., 1977) to correlate v taken alone with most geomagnetic indices proved ultimately disappointing (Crooker and Gringauz, 1993), whereas coupling functions which approximate frontside merging have much better predictive power when applied to commonly used geomagnetic indices (Burton et al., 1975; Wygant et al., 1983; Scurry and Russell, 1991; Newell et al., 2007).

Another factor in the reluctance to explore v as a substorm trigger may be that, after all, the variability the IMF and especially B_z far exceeds the variability of v, especially over the time scale of minutes to a few hours. The major component of the IMF lies in the Earth–Sun plane, with the north–south component erratic, crucial to merging, and virtually demanding investigative interest. By contrast, the auto-correlation of the solar wind speed from hour-to-hour is extremely high, so those interested in a specific trigger will quite rightly have concluded solar wind speed alone is not often likely to provide it.

Early explorations of solar wind conditions around the onset of auroral substorms suggested a "loading" phase, during which solar wind driving was enhanced (Caan et al., 1975). The same early work also suggested a possible trigger for onset. This is a "northward turning", or, as would be more generally understood today, a reduction in the solar wind-magnetosphere coupling function (which essentially means, an appropriate estimate of frontside magnetopause merging to the IMF). The history of attempts to validate these two early thesis has been quite different. The loading thesis has been repeatedly confirmed by those who examined the issue. Occasionally, attention paid to substorms occurring under steady northward conditions, and this perhaps suggests a violation of the rule of a loading prerequisite. However almost all such northward IMF substorms are in fact actually preceded by a loading phase when a coupling function that is more accurate than just the sign of B_z is used (Newell and Liou, 2011). Specifically, northward IMF substorms are just cases where $|B_y| \gg B_z$ (quantitatively, about 2–3 times larger seems to work). Thus when examined on the basis of, say, $d\Phi_{MP}/dt$, "northward" IMF substorms show the same loading as occurs for the more common southward IMF substorms. Thus both current theoretical and current observational understanding of the magnetosphere strongly support the hypothesis that substorms are preceded by a loading phase (e.g., McPherron, 1970; Shukhtina et al., 2005; Morley and Freeman, 2007; Boakes et al., 2009).

By contrast, the "northward turning" thesis has been buffeted by contradictory findings. Superposed epoch analysis studies invariably do show a statistical drop in solar wind driving beginning about 20–30 min before onset (Caan et al., 1975; Newell et al., 2001; Newell and Liou, 2011). Case examinations though have shown that individual substorms quite often lack a northward turning; it is only the ensemble average which consistently shows such behavior. This has led to the suggestion that the northward turning is a mean regression behavior (Morley and Freeman, 2007; Freeman and Morley, 2009). The idea is that since loading is a requirement before onset, driving must be high (often meaning B_z is negative), whereas at, or shortly before, onset that requirement is eliminated, so that the IMF should trend toward random, and therefore revert to mean values. The mean value of B_z is zero. Johnson and Wing (2014) took an entirely different approach, using information theory to investigate the extent to which a northward turning provides useful information about the likelihood of a subsequent substorm. Johnson and Wing (2014) concluded that a northward turning provides only minor information about subsequent substorm probability.

However support for the northward turning trigger hypothesis has also appeared. Lyons (1995) developed quantitative criteria for a reduction in solar wind driving that was theorized to precede most substorm onsets. Hsu and McPherron (2003) investigated 361 substorms and found that many were indeed triggered. However most were not actually triggered based on the Lyons algorithm rigorously applied but rather by additional criteria for solar wind changes added ad hoc (as indeed, was quite adequately described in Hsu and McPherron (2003)). Newell and Liou (2011) tried applying the Lyons criteria rigorously (mechanically) to a previously established set of auroral substorms identified from Polar UVI data, and found those conditions were no more likely before onset than at any random time. Therefore the northward turning signature has not yet been developed in a way that can described in a successful predictive algorithm. Newell and Liou (2011) also showed that when times of southward IMF are randomly superposed with a relaxation of constraint at an artificial $t=0$, the result is a "northward turning" very similar to superposed epoch studies of substorms.

2. Data and techniques

2.1. The SuperMAG SME (SMU, SML) indices

The auroral electrojet index, *AE,* was introduced by (Davis and Sugiura, 1966), using 5 magnetometer stations. One component, *AU*, is thought to represent the strength of the eastward auroral electrojet, primarily in the dusk cell. *AU* is defined as the maximum North–South component (called B_N here, as in other SuperMAG work, although traditionally labeled B_H) from among the contributing stations, Likewise, *AL*, defined as the minimum (most negative) B_N component represents the westward electrojet, with the contributing station usually located in the early morning. During substorm onset, however, the station observing the most negative B_N is usually in the dusk sector beneath the auroral