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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 expansion (e.g., Gjerloev et al., 2004). The *AE* index, $AE = AU - AL$, is calculated by the Kyoto World Data Center, with a fixed 12 station network.

Standardization has its advantages, but the relatively small number of stations creates limitations. Using just 12 stations to represent global dynamics is known to present problems (e.g., Rostoker, 1972). Newell and Gjerloev (2011a, 2011b) used SuperMAG to introduce auroral electrojet indices at a 1-min cadence for multiple decades using up to 130 stations. Because the 12-station *AE* index is an official IAGA product, an alternate name, *SME* ($= SMU - SML$) is necessary for the SuperMAG version. Nonetheless, conceptually *SME* may be regarded as *AE*(100). The *SME* index and ancillary data (such as the station contributing *SMU* and *SML*) are available from the SuperMAG web site at 1-min cadence. An important and sometimes unappreciated aspect of index construction is the creation of a baseline. Indeed, without a baseline, interpreting perturbations is of limited value. Gjerloev (2012) introduced a uniform and powerful method for this necessary normalization which is applied to all data before use in the construction of the indices studied here. *SME* is calculated using all stations contributing data to the SuperMAG project and which lie in the range 40° MLAT through 80° MLT. Fig. 1 of Newell and Gjerloev (2011a) shows the distribution of stations used in the initial calculations, along with a comparison to the range used for standard *AE*. Unlike the official *AE*, *SME* is never finalized, as any new data added may result in recalculations – as can indeed, improved noise removal.

2.2. Substorm identification

Our data base consists of about 40,000 substorms from January 1, 1997 through December 31, 2007, identified from the *SML* index. Details about identifying substorms from *SML* are given in Newell and Gjerloev (2011a), along with considerable verification versus satellite data. Therefore we give here only a brief summary. Substorms were defined by a drop in *SML* that was sharp (45 nT in 3 min) and that was sustained (−100 nT average for 25 min starting 5 min after onset). The timing of the *SML* identified substorms agrees reasonably well with Polar UVI, albeit with a median lag of about 4 min, with the magnetometer-identified onset lagging the imager identified onset. *SML*-identified substorms have the same characteristic and sustained increase in global auroral power as to Polar UVI identified substorms (Newell and Gjerloev, 2011a). This represents a considerable improvement on using the traditional *AL*(12) to identify substorms, as was also shown in that paper.

Other papers discussing the SuperMAG data base of substorm onsets and its reliability have recently been published (Newell and Gjerloev, 2011b; Newell et al., 2013), and further discussion here does not seem to be warranted.

2.3. Solar wind observations

For solar wind plasma and magnetic field parameters, which are used to determine the condition of solar wind driving, we use

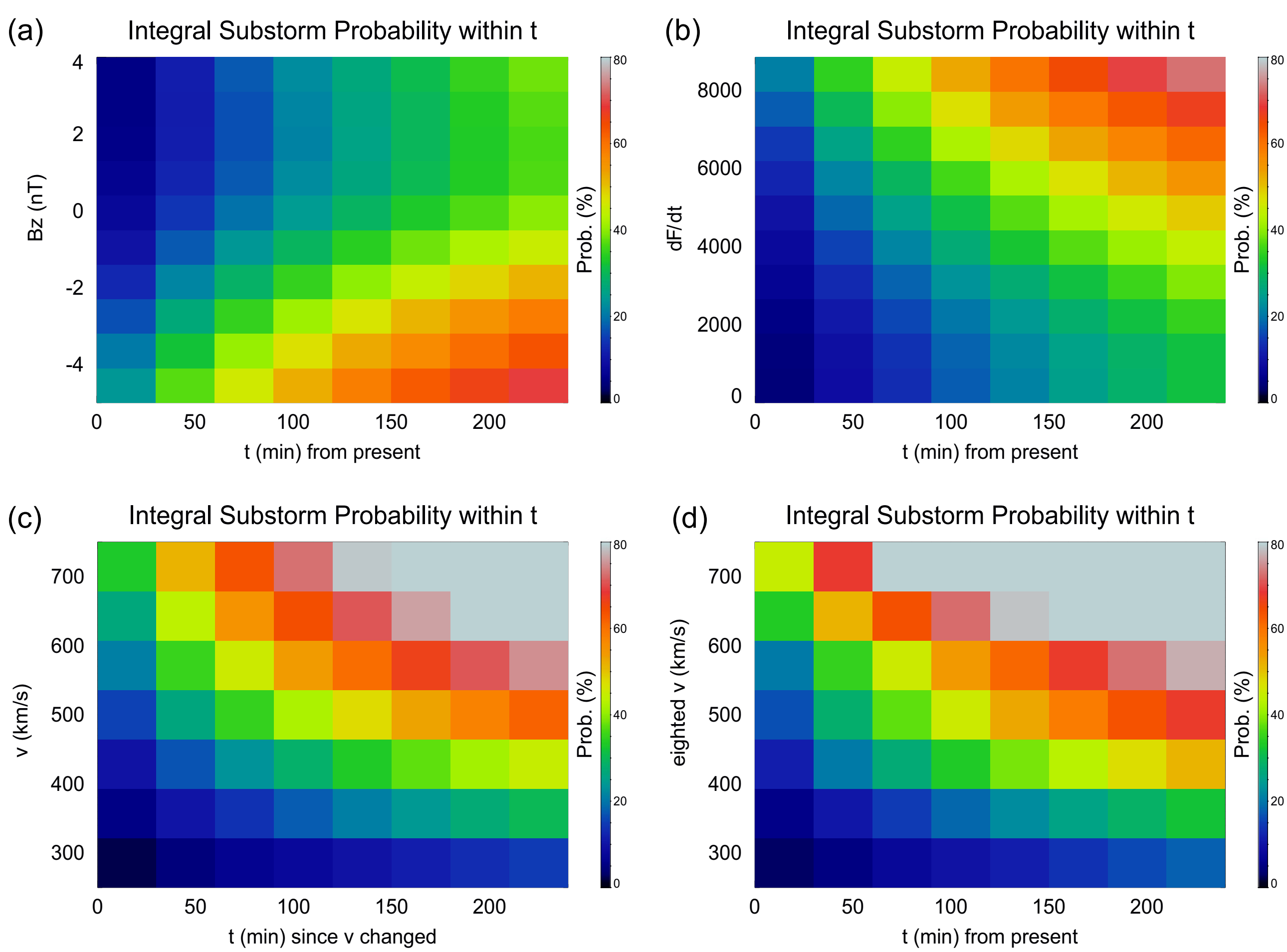

Fig. 1. Cumulative probability of a substorm onset occurring within a time, t (x-axis), after observing a specific (a) IMF B_z component, (b) frontside merging ($d\Phi_{MP}/dt$), (c) solar wind speed, and (d) time-weighted (see text for explanation) solar wind speed. The nominal units of the frontside merging are the awkward $(km/s)^{4/3}(nT)^{2/3}$, but an approximate conversion to Wb/s can be done by multiplying by $c_{MP} = 100$ (Cai and Clauer, 2013). Onsets are identified from the SuperMAG data base and the IMF is a 1-min value propagated to the bow shock.

1-min time resolution data from NASA's Space Physics Data Facility (SPDF) high-resolution OMNIWeb (HRO). Plasma and magnetic field measurements in upstream from the Earth's bow shock by Wind, IMP-8, and ACE spacecraft are prepropagated to the subsolar bow shock using minimum variance techniques developed by Weimer and King (2008). We add an additional 5-min lag to allow for propagation through the bow shock to reach the magnetopause.

3. Solar wind conditions and substorm probabilities

It is an understatement to say that previous work has been supportive of the need for a loading phase before a substorm. Indeed, current understanding of the magnetosphere and its dynamics would have to be widely amiss if an explosive release of magnetotail energy were possible without any storage before hand. This is demonstrated, after the initial work (McPherron, 1970), by a series of work such as the open flux in the magnetotail (Shukhtina et al., 2005) and the theory-based minimum substorm model (Morley and Freeman, 2007). More recently, superposed epoch studies uniformly support a loading phase before onset, as does a more detailed examination of the distribution of solar wind conditions before onset (Newell and Liou, 2011; Liou et al., 2013).

Nonetheless, it is useful to look at problems from multiple viewpoints, and also to try a new technique on a problem at least partially understood. The sign and magnitude of B_z is the single most important factor in the frontside merging rate, although today it is appreciated that B_y also matters (since a large magnitude B_y and small positive B_z also leads to merging near the frontside, albeit at higher latitudes (Crooker, 1979)). Since B_z is the oldest, most studied, and single most important merging factor, let us begin with how B_z affects substorm probabilities. Fig. 1(a) shows how the observation of B_z affects the probability of observing a substorm. Fig. 1(a) is calculated simply by stepping through time, starting from 00 UT on January 1, 1997, and looking at each value for B_z, and determining the time elapsed before the next substorm. The time step is 5 min, so there are 288 observation points a day (many of which are related to one another – nonetheless, the sampling is uniform throughout the whole year). Fig. 2a shows an example of substorm onsets identified with the SML index along with the concurrent solar wind speed (v) in Fig. 2(b) and the z-component of IMF (B_z) in Fig. 2(c). This particular example shows the first 12 h of a geomagnetically active day on January 11, 1997. Assuming the time bin starts at t=0300 UT the next time segment considered will start 5 min later, i.e., at t=0305 UT, and so on. The time segment, which is 4-h wide, is further divided into 8 subdivisions (bins) such that each time bin is 30 min wide. IMF B_z is measured at the starting time for each time segment. For example, B_z was −7.4 nT at 0300 UT and 0.7 nT at 0305 UT, as shown in Fig. 2(b). A total of 6 substorm onsets were found to occur in the first time segment. The onset partition to each time bin is straight forward. For example, there was no substorm onset in the first time bin (0–30 min), one onset in the second bin (30–60 min), and one in the third bin (60–90 min) etc. Since the onset number here is defined as cumulative, the substorm number is 0, 1, and 2 in the first, second, and third bin, respectively (see Fig. 2(a) inset). There was no onset occurring in the fourth and fifth time bins until the sixth, which we add one (i.e., 3) to this bin. The number in the seventh bin is 5 because there were 2 onsets occurring in this bin. We add one to the last bin because there was onset substorm in that bin. The onset partition to the next (t=0305 UT) and other time segments follows the same procedure as described above. To calculate the cumulative probability of substorms, substorm onset numbers that occurred in time segments that are associated with the same B_z bin are summed. Onset probabilities are calculated by

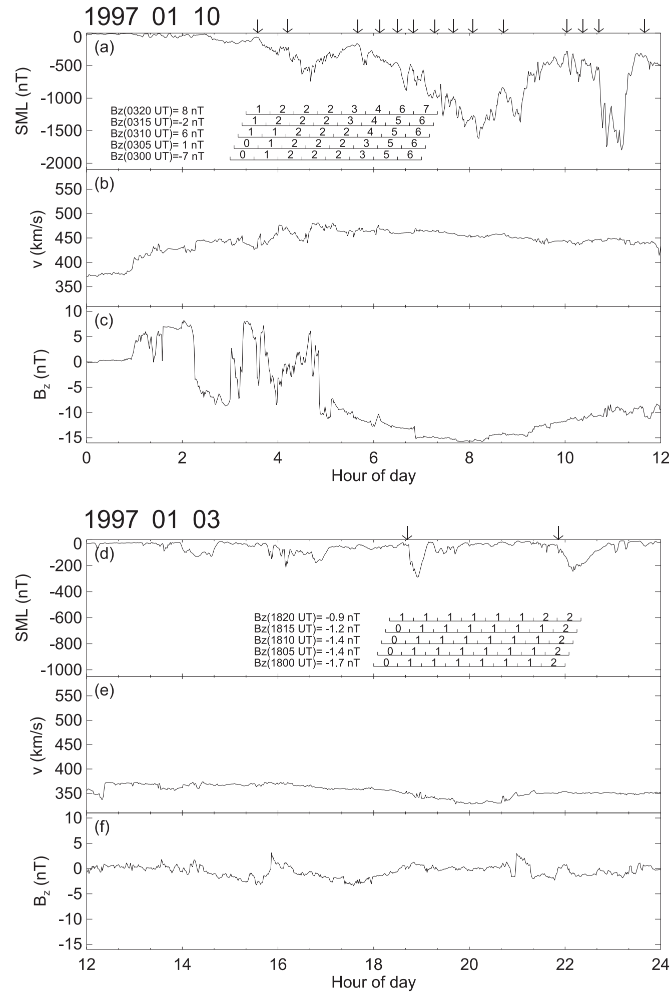

Fig. 2. (Top three panels) An example of magnetic substorm onsets identified from (a) the SuperMAG SML index for the first 12 hours of January 11, 1997. The z-component of interplanetary magnetic field from OMNI/HRO is listed in (b) for the same time period. Downarrows on the top of panel (a) mark substorm onsets. The insert in panel (a) shows how substorm onsets are counted in each time bin (see text for detailed explanation). (Bottom three panels) Another example on January 3, 1997, for a quieter geomagnetic activity, with the same format as the top one.

dividing onset numbers within each bin by the total of onset numbers in the time sector. The same procedure is used for the solar wind speed and other parameters. The selection of this (geomagnetic storm) event is purely for demonstration purposes. Fig. 2(d) show another example on January 3, 1997. In contrast to the previous example, this event is relatively geomagnetically quiet, as indicated by small values in the *SML* index. This time period is probably more typical as it is associated with a slower solar wind (Fig. 2(e)) and less fluctuated IMF B_z (Fig. 2(f)) relative to the previous example. As expected, the cumulative probability of substorms is evidently smaller (see the inset in Fig. 2(d)).

Thus in Fig. 1(a), B_z is the current 1 min value (t=0, based on propagation to the bow shock). The x-axis in Fig. 1(a) is the time elapsed after observing B_z, while the y-axis is the magnitude of B_z as of the original observation point. One then determines the time required for the first subsequent substorm onset to occur (in the SuperMAG data base). The probability plotted is cumulative and thus monotonically increasing.

Fig. 1(a) shows that knowing just the current value of B_z does have predictive value, although at a modest level. As expected, the more negative B_z is, the greater the odds of a substorm. If B_z=0 nT, the odds of a substorm within 90 min is about 25%, while if one observes $B_z = -4$ nT, the odds rise to about 56%. The effect of a northward IMF does reduce the odds of a substorm, but not as much as a southward IMF increases it, primarily because a measure of substorm loading based on B_z alone is limited. The point is that if B_z is southward, loading is certainly occurring, whereas if it is northward, loading may or may not be occurring (as is true also for $B_z = 0$). Over an extended period of time (90 min) the difference in probability of a substorm after observing a modest positive B_z and $B_z = 0$ is minor.

Fig. 1(b) shows a similar plot, except using a more modern estimate of the frontside merging rate, namely $d\Phi_{MP}/dt = c_{MP}v^{4/3}B_T^{2/3}\sin^{8/3}(\theta_c/2)$ (Newell et al., 2007), and time integrated according to the formulas given therein for AL ($w = 0.69^n$, $n = 1$, 2 and 3). Here θ_c is the IMF clock angle and $c_{MP} = 100$ normalizes the expression to produce Wb/s if the IMF transverse to the Earth–Sun line, B_T, is in nT, and v in km/s (Cai and Clauer, 2013). Fig. 1(b) shows that a high frontside merging rate does produce a higher probability of substorms, but a low merging rate (unlike a northward IMF) produces a very low probability of substorms. In other words, the chances of a substorm without loading is quite low. The probability of observing a substorm within 90 min (third column) after observing $d\Phi_{MP}/dt$ equal to about twice the solar wind mean value (e.g., ~8000 (Newell et al. (2013))) is 52%. If $d\Phi_{MP}/dt$ is about half the solar wind mean value, the odds of subsequently observing a substorm is about 17%.

So far this approach has not produced dramatic surprises. The behavior of Fig. 1(a) and (b) accord well with the results of previous research on substorm loading. However one purpose of this paper is to test whether v, considered alone, has a high impact on the probability of substorm occurrence. Fig. 1(c), then, shows the odds of observing a substorm in the time following a given observed value of v. The effect of a higher v is substantially more dramatic than a more negative B_z or higher $d\Phi_{MP}/dt$ (despite the fact that the latter incorporates v). The y-axis scale covers less than twice the long-term mean value (430 km/s (Dmitriev et al., 2009)), and therefore Fig. 1(a)–(c) as a whole are perhaps biased against v. Even so, the difference between substorm probabilities for low v and high v are significantly more dramatic than low and high merging rates. To quantify this, consider the time bin starting 90 min out (90 min–120 min after observing a given v). For initial v within the bin 250–321 km/s, the chances of a substorm are just 10%. For v between 679–750 km/s the chance of a substorm having occurred by the 90–120 min bin is 80%. If a time-weighted average of v is used ($w = 0.69^n$, $n = 1$, 2 and 3) (Newell et al., 2007), these figures will jump from 12% to 94% (see Fig. 1(d)). Essentially, if the solar wind speed is low, a magnetospheric substorm is unlikely; if high, fairly certain. The v effect is much more prominent than other possible solar wind combinations, even those that incorporate v into more complex functions.

The solar wind dynamic pressure is intimately linked with speed, as $p = m_p n_p v^2/2$, where m_p is the proton mass, and n_p the proton density (we are not here concerned with the minor corrections due to the small admixture of He^{++} and so forth). Pressure is a fundamental component of the solar wind, shaping the magnetosphere (e.g., Roelof and Sibeck, 1993), and implicitly determining pressure within the magnetotail via pressure balance. It is important therefore to determine whether p perhaps has an even greater effect on substorm probabilities than v (which would imply v is an indirect correlate, as both onsets and v would be related to p). Thus Fig. 3 shows the odds of a substorm following the observation of a given dynamic pressure value in the same format as Fig. 1. Although p does have a moderate ability to predict substorm onsets, it is markedly below that of v, and therefore we infer that the correlation with p actually arises from its connection to v, and not the other way around.

In current theoretical understanding, the effect of v should be the result of its effect on merging rate, and B_z plays the starring role there

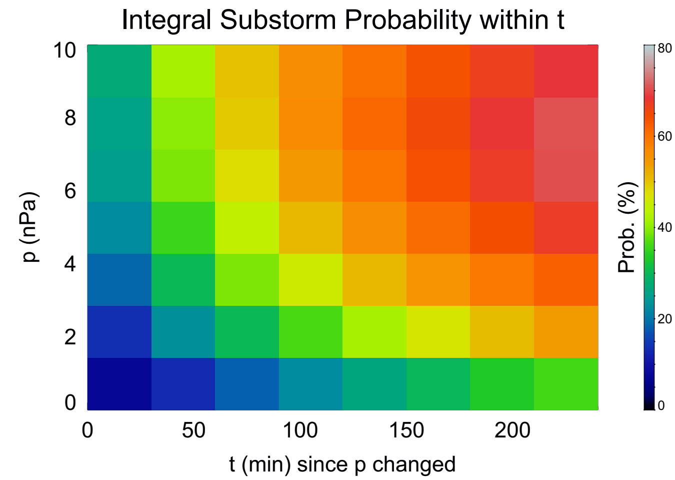

Fig. 3. Same as Fig. 1, except using solar wind dynamic pressure, p, for the y-axis. Although p is closely related to v, p has less of an effect on substorm probability than does v.

(followed by B_y). For v alone to be a better predictor of substorm onset than is, say, vBs or $d\Phi_{MP}/dt$, is the major finding of this paper.

4. Changes in solar wind driving and substorm probabilities

As previously mentioned, there are many conflicting results in the literature concerning how IMF changes before onset, or how these changes might trigger instabilities. Let us consider what our methodology produces following changes in the IMF. The most classic – in the sense of the oldest and most frequently mentioned – change is a northward turning in B_z preceding substorm onset. Let us therefore examine whether an increase in B_z (which need not necessarily actually be positive after the change) does, in fact, alter the odds of observing a substorm onset.

Fig. 4(a) shows the probability of observing a substorm onset following a change in B_z compared to the preceding 20 minutes. The change is calculated by comparing IMF at a fixed interval of 20 min. Thus the algorithm steps through the entire time interval studied (1 Jan 1997–31 Dec 2007) in 5 min increments. At each step the current 1-min B_z (at current time t_c) is compared with the 1-min value at $t_0 = t_c - 20$ min. The time until the next substorm recorded in the SuperMAG data base is computed starting from t_c. This means that if one measures a current B_z that differs from 20 min ago, Fig. 4(a) shows that the probability of a substorm subsequently occurring. For completeness, both positive, negative and no change are considered and plotted, although it is the positive change usually cited in the literature.

Interestingly, both positive and negative changes in B_z make a substorm more likely than does continuation of existing conditions. However a change toward northward (thus a reduction in solar wind driving) creates a higher probability of a substorm than does a negative (more southward IMF) change. This provides some limited validation to the northward turning hypothesis. Nonetheless, the magnitude of the observed effect is moderate, as a positive change of B_z enhances the odds of a substorm over the next 100 min modestly. Quantitatively, after 90 min, the chance of a substorm having occurred with no change is 24%, with a negative change of –2 nT 28%, and after a positive change (of +2 nT) 40%. Perhaps this result will not satisfy anyone, since it does show a northward turning increases the odds of a substorm, but it does not have a dramatic effect.

Fig. 4(b) examines the effects of a change in a more general estimator of frontside merging, namely $d\Phi_{MP}/dt$. When comparing

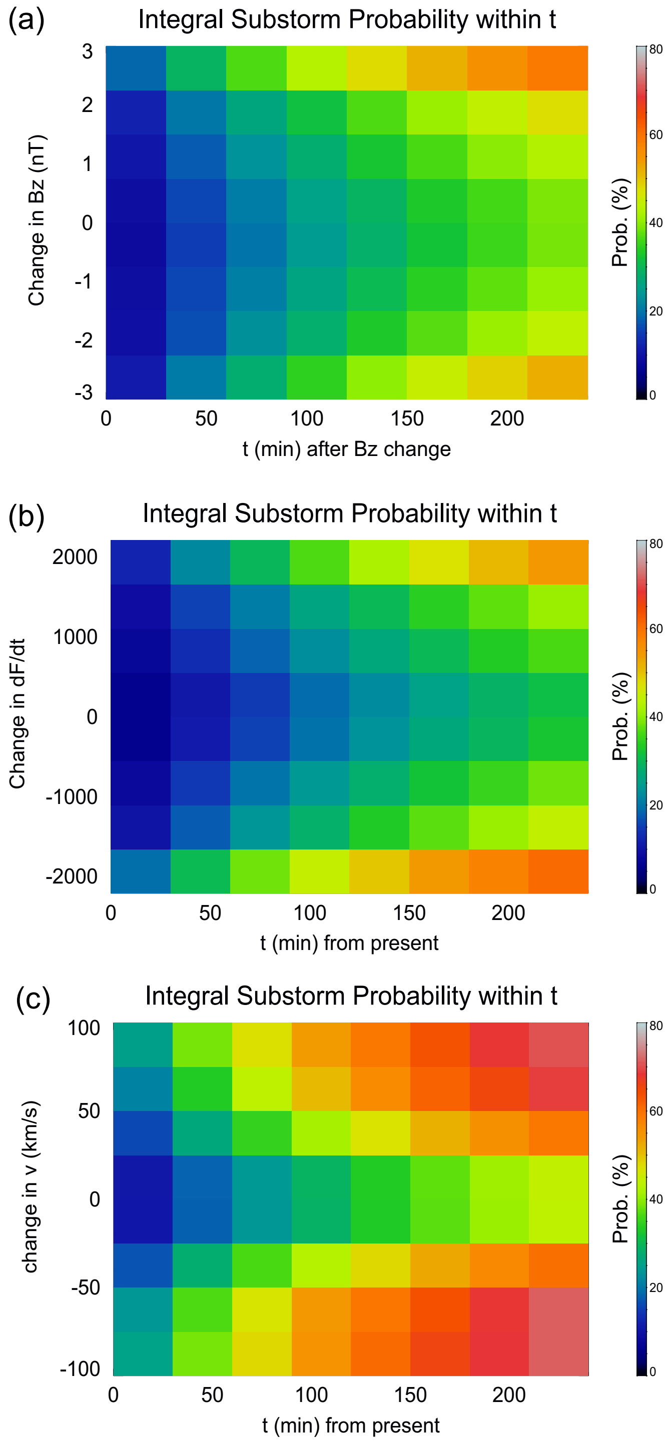

Fig. 4. The effect of a change in (a) IMF B_z component,(b) frontside merging, $d\Phi_{MP}/dt$, and (c) current v on the cumulative probability of a substorm. Any change increases the odds compared to no change, with a northward turning (positive change) creating the greater increase. However the magnitude of the effect is much smaller than for v.

with Fig. 4(a), a reflection across the *x*-axis is necessary, as a more positive B_z corresponds to lower solar wind driving (hence smaller $d\Phi_{MP}/dt$). The two figures are suite similar, although, as expected, $d\Phi_{MP}/dt$ produces a stronger effect (as a better estimator is likely to do for a real phenomenon). The scale of the change plotted in Fig. 4(a) is modestly larger than for Fig. 4(b) as a fraction of the long term standard deviations, so there is not a bias against B_z changes. In any case, a reduction in solar wind driving, however calculated, is still associated with a stronger increase in substorm probability than is enhanced driving.

Nonetheless, this "northward turning" effect is still less than overwhelming. Taking 60–90 min after t_c (after completing a change in $d\Phi_{MP}/dt$) as our illustrative epoch again, we find that a change of $+2\times10^5$ Wb/s in frontside merging produces a 30% chance of a substorm. No change means a 17% chance by the 60–90 min bin, while a negative change (reduced merging, equivalent to a northward turning) of -2×10^5 Wb/s produces 39% chance of a substorm having occurred. Clearly any change in solar wind conditions improves the odds of a substorm, but a reduction in merging seems to have the bigger effect.

Finally, we consider the effects of a change in solar wind speed. The major result of Section 3 was that v is the best solar wind predictor of subsequently observing a substorm, not the merging rate. Fig. 4(c) shows that changes in solar wind speed produce a more dramatic increase in substorm probability than do changes in B_z, or even $d\Phi_{MP}/dt$. Notice the change in speed covered on the plot is only about 10% of the mean value. The reason is that 10% changes in v occur roughly about as often as the other changes. Once again a change toward lower v has a bigger effect on substorms than does a shift toward higher speeds (even though, as Fig. 1(c) showed, higher speeds are intrinsically linked with higher substorm probabilities). The magnitude of the effect of a change in v is greater than that found for B_z or $d\Phi_{MP}/dt$. For example, the odds of observing a substorm within the illustrative 60–90 min bin after a change in v of -100 km/s is 49% (an increase of $+100$ km/s gives about the same result, 48%). If there is no significant change in v (in the last 20 min) the odds are 24%. This is a meaningful level of influence, although the substorm odds after such a v decrease are still less than the probability inferred from a high starting v (Fig. 1(c)). After considering a variety of solar wind circumstances, the single best determinant of the chance of subsequently observing a substorm remains the current observed value of v.

Occurrence of substorms is known to be modulated by high-speed solar wind streams (e.g., Tanskanen et al., 2005). To avoid a potential bias, we divide data into two groups: 1999–2002 and 2004–2007. The first group represents solar maximum years when coronal mass ejections are frequent, whereas the second group represents the decline phase when the high-speed streams originating from the coronal holes are frequent. Fig. 5 shows substorm probability for the two periods for $d\Phi_{MP}/dt$ and v. In general, substorm occurrence is, as expected, slightly higher in 2004–2007 than in 1999–2002 for both predictors. When comparing the substorm probability between $d\Phi_{MP}/dt$ and v, it is clearly shown the solar wind speed is a better substorm predictor than $d\Phi_{MP}/dt$ for both periods. This is also true for yearly data from 1997 to 2007 (not shown).

5. Discussion: magnetosphere driving, merging estimators, and v

Several questions naturally rise from the key result of Section 4, namely that the magnitude of v is the best determinant of whether a substorm subsequently occurs. The magnetosphere has, one presumes, not changed its dynamic behavior. So the first question to consider is why has the critical importance of v in substorm onset not been previously noticed? Next, what about the overwhelming evidence accumulated over several decades that frontside magnetopause merging drives most magnetospheric activity? Finally, if v determines substorm onset likelihood, and frontside merging drives the energy input into the magnetosphere, which phenomena depend more on v, and which upon frontside merging? Let us take these issues in turn.

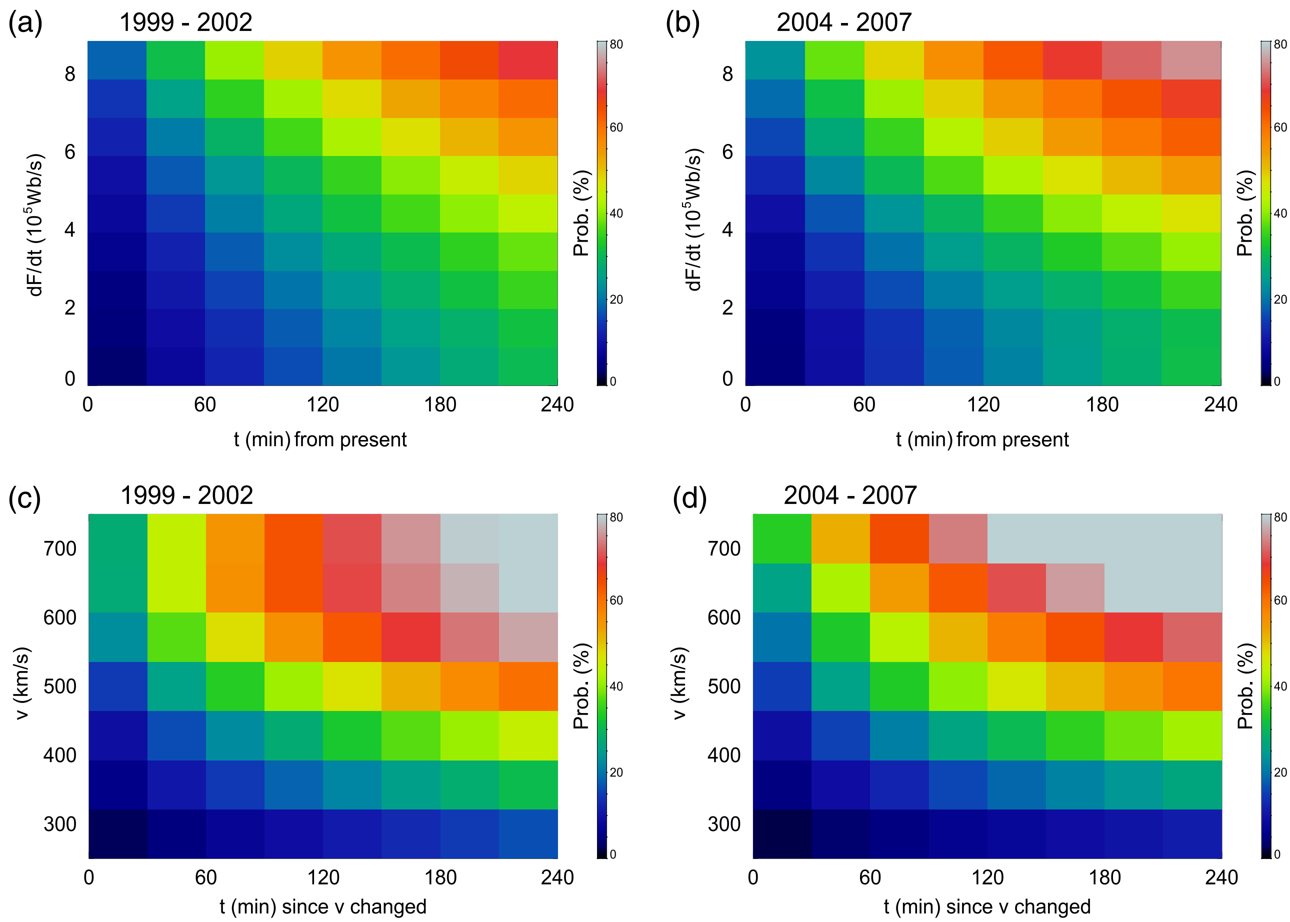

Fig. 5. Same format as Fig. 1, except for (top) frontside merging and (bottom) solar wind speed and for solar maximum years, (a and c) and for solar cycle declining years (b and d).

5.1. *Substorm likelihood, v and published research*

The bias toward considering B_z and merging rather than v when investigating substorm triggering is actually logical considering advances made in magnetospheric research over the last few decades. As long as solar wind measurements have existed, observations have supported the association between southward IMF and geomagnetic activity, while theoretical progress on magnetic merging as well as in situ observational details at the magnetopause have also pointed toward the importance of merging. Although some coarse time scale correlations of geomagnetic activity with the solar wind did indeed identify solar wind speed as a crucial determinant (Crooker et al., 1977), this correlation did not hold up over subsequent solar cycles (Crooker and Gringauz, 1993). In fact, v by itself is a poor predictor of geomagnetic indices – or AP as inferred from global imaging, or cusp latitude, or magnetotail stretching – at a time scale of 1 h or less (Newell et al., 2007).

Given the theoretical and observational support for merging, then, it is perhaps not surprising that the first superposed epoch analysis of substorms (Caan et al., 1975) plotted the behavior of B_z around substorms, but did not plot v. What Caan et al. (1975) did find, however, was that B_z averaged distinctly southward before onset but trended back toward zero after onset. It is now established that this reversal is, at least in significant part, a result of the requirement of a magnetotail flux loading phase before a substorm, followed by the absence of an imposed criterion after onset, leading to a reversion toward mean (which is $B_z=0$). The reversion mechanism was suggested by Freeman and Morley (2004) and observationally supported by Newell and Liou (2011). The northward turning does not show up in most individual cases of substorm onset. Rather it is a consistent feature of superposed epoch studies, both in early work and later studies. Thus much of the later theoretical (Lyons, 1995; Morley and Freeman, 2007; Freeman and Morley, 2004) and observational (Lyons et al., 1997; Hsu and McPherron, 2003; Freeman and Morley, 2009; Newell et al., 2010; Johnson and Wing, 2014) work has focused on the question of changes in B_z or merging rate (such as vBs).

It should be kept in mind that the relaxation time after an observation of high v is quite slow, primarily because of the long autocorrelation time of v. That is, the relaxation to mean after onset should occur over many hours, not just tens of minutes, as in the case of B_z. Therefore the search for a specific "trigger" in the solar wind would naturally lead away from v, which is typically little changed around onset. It is nonetheless the case that substorms are much more likely if v is high.

The subject may also have been influenced by a preference for studying well isolated substorm onsets. A prolonged period without an onset is very likely a time of no higher than average v. The data base of Polar UVI onsets (Liou, 2010) is skewed toward isolated onsets, which then biases a study such as Newell et al. (2010) toward v which is no higher than the mean. This is probably true of several other studies as well, since the preference for isolated onsets is pronounced in magnetospheric research.

Finally, another thread of evidence comes from steady convection events. Published events tend to be for relatively modest solar wind speeds, and this appears not to be an accident. The survey by Partamies et al. (2009), for example, shows that "solar wind velocity below 400 km/s" is the "hallmark" of steady magnetospheric convection intervals. Since that is essentially the mean solar wind speed, this means that steady convection occurs when the solar wind speed is below its mean. This result also is in good accordance with the results of this paper, as Fig. 1(c) makes clear that a solar wind speed above the mean makes substorm probabilities too high for steady convection.

5.2. Why does onset probability depend so strongly on v?

Clearly v is a fundamental aspect of the solar wind, determining (along with density) dynamic pressure and (along with the IMF) the frontside merging rate, as well as being a major factor in determining the rate of flux transport into and through the magnetosphere. However since v considered alone predicts the likelihood of a subsequent substorm better than does combining it with other parameters to get dynamic pressure or frontside merging rate, we argue that attention should be focused on the final of these effects, namely the rate of flux transport.

The issue of how flux can be transported stably through the magnetotail has been vexing at least since Erickson and Wolf (1980) pointed out the difficulties in conserving the adiabatic invariant under steady convection from the distant tail to near Earth. The resulting pressure in the near Earth region would be implausibly large. Over time, an appreciation has grown that highly variable flux transport (e.g., Angelopoulos et al., 1993, 1996) is more the norm than is steady convection. There are several possible ways in which a flux tube can reduce the transport catastrophe outlined by Erickson and Wolf (1980). Precipitation losses are one such mechanism. Convection in the magnetotail can ultimately be strongly related to convection in the magnetosheath and solar wind, both theoretically and observationally (Borovsky et al., 1998). Solar convection in the magnetotail gives more time for mechanisms maintaining equilibrium to act. This is true of the previously mentioned precipitation loss mechanism, and more generally for other adjustments within the magnetosphere.

A change in solar wind conditions, namely v, $d\Phi_{MP}/dt$, and P, also increases the odds of a substorm, albeit to a markedly lesser extent. The secondary effect changing v (or B_z) has on increasing substorm probability also suggests that the issue is the ability of the magnetosphere to adjust. Normally the IMF is quite variable. This variability may tax the ability of the magnetosphere to adapt, and it may be particularly hard for the magnetosphere to keep up when convection speeds are higher.

Perhaps the most promising avenue to explain these results comes from MHD simulations. Both Goodrich et al. (2007) and Pulkkinen et al. (2007) have used the Lyon–Fedder–Mobarry MHD model to investigate specifically the stability and behavior of the magnetotail under varying solar wind velocities. These authors do find that higher speeds create much more unstable conditions and bursty behavior. It is possible that this work can pin down how high solar wind speeds produce so many substorms.

This is hardly intended to be a definitive answer – or indeed a significant investigation – into the observational dependency established in this paper. In fact, there are a large number of substorm theories (Lui, 1991), and many theories such as the Kelvin–Helmholtz velocity related shears seem to work better an higher velocities (Yoon et al., 1996). Nonetheless, future studies of substorm triggering should take into account the strong dependence on v reported here.

5.3. Frontside merging, geoeffectiveness, and v

The “geoeffectiveness” of particular solar wind conditions is sometimes debated, including whether geoeffectiveness depends on the specific magnetospheric phenomenon considered. Many phenomena, including AP, *Dst*, and most geomagnetic indices such as *Kp*, are best determined by solar wind functions which serve as estimators of frontside magnetopause merging. This has been shown by various authors in a variety of ways (Burton et al., 1975; Boyle et al., 1997; Wygant et al., 1983; Scurry and Russell, 1991), with the most comprehensive study covering multiple measures of geomagnetic behavior over many decades by Newell et al. (2007). The function *vBs* is occasionally considered to be distinct from the explicit merging estimators as it has units of electric field, yet it functionally varies quite similarly to the Sonnerup (1974) formula for frontside merging rate (Wygant et al. (1983)). Any of these various estimators of frontside merging better predict AP and related geomagnetic indices much more accurately than does v taken alone.

Yet v by itself does work best for a few phenomena, most notably the radiation belt energy flux (Li, 2005). We have here shown, for the first time, that substorm onset probabilities are also better predicted by v alone rather than by more complex functions which also including the IMF. That finding supports the hypothesis investigated in this paper about how these distinctions in geomagnetic response arise. The importance of v in driving the magnetosphere should not be overstated. We do not dispute that most magnetospheric phenomena track frontside merging, at least looked at on a coarse scale, heavily filtered by internal magnetospheric dynamics. Thus v (excepting its role in as a component of a decent merging estimator) does not regulate energy flow into the magnetosphere. The effect, rather, in upon whether AP is dissipated smoothly, or in bursts.

Each substorm onset involves a rapid dipolarization and that in turn will create high-energy tail electrons which further dipolarizations and enhance. Of course a higher solar wind speed means that higher energies are available in the magnetotail to begin with, (Baker and Kanekal, 2008; Baker et al., 2014). But the association with substorm onsets found here means that, in addition, and perhaps more crucially, a higher v means more substorm associated dipolarizations (Tanskanen, 2009) and thus more often repeated electron acceleration cycles.

5.4. Some insights from quiet and active years

By some measures the year 2009 was extraordinarily geomagnetically quiet, although that status appears to depend upon the method in which activity is measured. Using the same SuperMAG data base employed in this paper, Newell et al. (2013) found that there were just 448 substorms in 2009, versus a peak of 3727 substorms in 2003. These are the extrema for the three decades covered in the SuperMAG data base. The variations in the usually considered parameters, such as *Bz*, *vBs*, and $d\Phi_{\mathrm{MP}}/dt$ cannot account for the exceptional difference in the number of substorms between these years.

One explanation sometimes proffered is that the low v solar wind has less extrema than does the high v wind (such as often occurs in the declining phase after solar cycle peak). Unfortunately that can only explain a portion of the large variation in substorms observed. Newell et al. (2013) examined the detailed probability distribution functions (PDFs) of solar wind driving conditions and found that none of the merging estimators could account such extreme variation in substorm occurrence. In contrast, the PDFs of v did seem to account for the yearly variations. For example, in 2003, v spent 75.6% of the entire year above its long term mean, but in 2009, v was above the long term mean just 12.3% of the time. None of the merging indicators had a difference at all comparable – or sufficient to account for the difference in substorm rates.

6. Summary and conclusions

Most magnetospheric phenomena, including auroral power, the energy stored in the ring current, magnetotail stretching, and so forth, correlate strongly with reasonable estimators of the frontside merging rate. However the radiation belt electron energy flux follows a simpler dependency, correlating best with just v. Here we have investigated a possible explanation for this seeming discrepancy. Specifically, whether the probability of observing a substorm depends strongly on v was investigated. The results strongly support this conjecture. Indeed, the currently observed v, taken by itself, better predicts the chance of onset in the near future than does a frontside merging estimator – even though these generally incorporate v into a more complex function.

Radiation belt electrons are thought to be associated with repeated magnetotail dipolarizations (Meredith et al., 2001, 2003), through a two-step process (Boyd et al., 2014). This produces a different solar wind dependency than phenomena which depend mainly on how much frontside merging loads energy into the magnetotail. AP can be strong for prolonged times without a substorm (cf. Shue et al., 2002). Conversely, it is likely that substorm onsets have either minor effect (Newell and Gjerloev, 2012) or even no effect (Ohtani et al., 2005) on ring current intensity. So while substorms modulate the rate of energy dissipation, they may not strongly affect the total power involved in aurora or the ring current. Therefore while a few phenomena, notably radiation belt fluxes, may depend on v, because that controls the frequency of dipolarizations, most phenomena will be predicted best by estimating the frontside merging rate.

The classical, and long debated, substorm triggering by a northward turning of the IMF does receive a modicum of support in our results. Specifically, any change in v or B_z does increase the odds of a substorm when compared to no change. Moreover, a drop in v, or, especially, a more northerly B_z (more generally, lower frontside merging) is more likely to be followed by a substorm than is a change to a higher v or a more negative B_z. This does fit with the idea on how some substorms are triggered by reductions in driving. However the "Northward turning" effect is distinctly secondary. The absolute magnitude of v is the single best predictor for whether a substorm will soon ensue.

Finally, the results of this paper shed light on other magnetospheric physics topics. It is now clear why steady magnetospheric convection events occur only for solar wind speeds below the long term mean (O'Brien et al., 2002). For speeds above the mean, the probability of a substorm is high, meaning dipolarizations events will occur. Likewise, the occurrence of years with very few or a great many substorms tracks solar wind speed more closely than variations in the distribution of drivers of frontside merging (Newell et al., 2013). Finally, one must be aware that an isolated substorm – one preceded by, say, 3 h without another substorm – is typically likely only if v is at or below its mean value, and thus represents one particular aspect of magnetospheric dynamics. The critical dependence of onset probability on solar wind speed must therefore be taken into account when studying a wide variety of magnetospheric behavior.

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