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A New Model for Near-Earth Magnetospheric Substorm Onset: Increasingly Parallel Pressure Anisotropic Ballooning

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Ballooning instabilities have historically been linked to near-Earth magnetospheric substorm onset in the region of earthward pressure gradients in the transition region between tail-like and dipole-like magnetic fields. Recent observations demonstrating that auroral beads are observed prior to the majority of substorm onsets (Kalmoni et al., 2017) have reinforced this link. Here we examine a new model for onset which invokes a key role for increasingly parallel pressure anisotropy. In the context of this new paradigm, we analyse the conditions under which such unstable ballooning mode instabilities can form. We adopt the model developed by Chan et al. (1994), and which takes into account pressure anisotropy, pressure gradients, and plasma β, among other parameters, and examine instabilities which may arise during transitions from perpendicular towards parallel pressure anisotropy, but which do not necessarily have to reach the level of a parallel anisotropic pressure distribution. Our results show that the plasma β threshold for triggering this branch of the ballooning instability can be lowered by moving from an initially perpendicular anisotropic distribution toward parallel anisotropy. Significantly, this effect becomes even more pronounced in regions of larger pressure gradients. To examine the conditions that may lead to such a change in anisotropy, we further trace particles through a model magnetic field with an increasingly stretched tail. Under the assumption of conservation of the first and second adiabatic invariants, we show that well-known drift-shell splitting occurs. The effect is to naturally increase the parallel anisotropy in the increasingly stretched tail fields, a region of relatively high pressure and large pressure gradients, exactly as required to trigger growing parallel anisotropic ballooning. This occurs due to a combination of reduction in pitch angles and transport of particles from regions of higher pressure but lower gradient to the region where these growing parallel pressure ballooning instabilities become maximally unstable. Our new paradigm for substorm onset therefore not only naturally generates unstable conditions towards the end of the growth phase, but it also predicts a localised and narrow magnetospheric onset location. In combination, our results suggest a new mechanism for substorm onset that is consistent with the known substorm time sequence of many well-known ground-based and in-situ observations, but which have heretofore not been causally linked to the near-Earth triggering of substorm onset.