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Reply

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In their comment, *Rodger et al.* [1994] (hereafter REA), make the point that more than one mechanism is likely to be involved in the production of polar cap density patches. While we would readily agree with this, we feel REA misinterpret important aspects of the mechanism we proposed [*Lockwood and Carlson*, 1992], and this leads them to dismiss it as a major source of patches.

REA argue that there are insufficient pre-existing gradients in the plasma density outside the polar cap for the model we propose to explain patch production. This is partly because they assume that our mechanism requires the day/night terminator to lie in a specific position relative to the equatorward edge of the convection pattern which is rarely achieved (and does not apply to the three examples we presented). We do not agree with their argument for three reasons:

1. In a true time-dependent model, such as that we proposed, the loci of flux tubes can diverge, converge and even cross [*Lockwood*, 1993]. (Naturally, flow streamlines never cross, but the flux tube loci and the streamlines are not identical for anything other than steady-state cases or unrealistic quasi-steady approximations). For example, if we only consider a time-dependent transpolar voltage, without allowing for associated evolution of the pattern of flow, the flux tube loci are not altered - the flux tube speeds simply vary as a function of time. By contrast in our model, the pattern of flow is time-dependent and flux tube loci converge on entering the polar cap (by more than the streamlines in any one flow snapshot) which means that the gradients on the edges of the patches exceed those outside the polar cap.

2. It is, however, true that the amplitude of the difference between the densities inside and outside patches must, for our mechanism to work, be present somewhere outside the polar cap. REA argue that our model requires that this range must be in a latitudinal structure lying within a narrow band less than about 3° wide, at the equatorward edge of the convection pattern. They reach this conclusion because they have not appreciated a key difference between the *Anderson et al.* [1988] model and the one we present. That is, they (explicitly) assume that our model works by simply expanding the low-latitude edge of the convection pattern equatorward. This is not the case. Our model considers how the sequences of changes in the dayside flow pattern, due to pulsed reconnection as predicted by *Cowley et al.* [1991] and *Cowley and Lockwood* [1992], effects the loci of flux tubes throughout the dayside convection region. Hence it can convert any pre-existing plasma density gradients (outside the polar cap but poleward of the region of complete co-rotation) into patches (inside the polar cap), and the original gradients can be either with latitude or local time. The patches arise because flux tubes which become adjacent in the polar cap have different loci and hence originated from significantly separated locations outside the polar cap. The required density gradients can lie anywhere in the region of dayside convection and do not have to lie close to the equatorward edge of the convection pattern, as REA assume.

3. In our paper, to illustrate the principle, we did use an initially straight plasma density contour aligned with a contour of constant solar zenith angle and the day-night terminator. However, we did also comment that this applied only to an idealised situation where convection had been absent for some considerable time before the first pulse of reconnection. In general, we would expect there to have been convection (in part driven by tail reconnection) in this period and this means that the true distribution of F-region plasma outside the polar cap will usually be considerably more complex than in the idealised case we presented. One such effect is seen in the afternoon sector, where the sunward convection of low density plasma from the nightside has been observed to extend the winter and equinox mid-latitude trough to low solar zenith angles (sunward of the day-night terminator) on the dayside. For example, *Willis et al.*, [1986] used the EISCAT radar to observe 100% density changes at the edges of the mid-latitude trough near 14 MLT in October. These spatial variations of the plasma density are therefore of the required amplitude, and in the required location, to give polar cap patches using our model. *Foster* [1993] has recently discussed other density gradients which are produced by convection on the dayside and which would, by our mechanism, act as a source of polar cap patches.

Hence, when we consider other sources of plasma density gradient, it is not true that our model requires the day-night terminator to lie in a specific location. On the other hand, the amplitude and occurrence frequency of gradients outside the polar cap (and hence also, by our mechanism, of the consequent patches within it) will be modulated by the position of the terminator. This means that all the examples we presented (which were for October and December) could be produced by our mechanism. It also means that our model predicts conjugate patch formation - at least around the equinoxes (as in the example cited by REA, which was presented by *Baker et al.* [1989]). At the solstices, the dayside mid-latitude trough in the summer hemisphere is filled in by the longer residence times of the sunward-

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convecting flux tubes in daylight; however, the gradients described by *Foster* [1993] could still give some (albeit weaker) patches. Hence we predict that patches should become less common and of smaller amplitude in summer, as reported by *Buchau and Reinisch* [1991].

REA cite some observations polar cap patches forming within 3 min. of a change in IMF B_y, and they state that enhanced plasma density cannot have convected over the necessary distances. If the appearance of a patch is not due to convection into the field of view, it must be due to in-situ processes. However, the time constants for the production of a typical peak density in a patch by precipitation, and for the generation of a typical minimum between patches by enhanced plasma flows, are usually considered to be much greater than 3 min. [see *Roble and Rees*, 1977 and *Moffett et al.*, 1992, respectively]. On the other hand, the time constant for the appearance of a patch, due to pre-existing density gradients, is simply the time to convect into the field-of-view of the instrument. If IMF $|B_y|$ is large (and $B_z < 0$), the flow speed in this region usually exceeds 2 km s^{-1}, enabling plasma to convect at least 360 km in a period of 3 min. This is sufficient to bring high density plasma into the field-of-view of an ionosonde or an HF radar. It is not sufficient to have brought it all the way from a region of plasma production by EUV radiation, but that is not a necessary condition as convection of some form existed prior to the IMF B_y change. Hence, the evidence published in the literature suggests that an IMF B_y change will be associated with the appearance of a patch because it causes a convection change which, in turn, causes enhanced plasma density to start to convect into the field of view, where it did not before. We would argue the rapidity of the response REA quote argues against, not for, in-situ generation of the enhanced plasma densities within patches.

Summary

In conclusion, there is a considerable body of evidence in the published literature which supports the concept that the enhanced plasma density in polar cap patches is mainly produced by solar EUV radiation and convected antisunward [e.g. *de la Beaujardiere et al.*, 1985; *Tsunoda*, 1988; *Buchau and Reinisch*, 1991; *Foster*, 1993]. Particularly significant in this respect is the observed solar cycle, seasonal and diurnal variations of patch occurrence. That anti-sunward convection and magnetic reconnection play crucial roles is signalled by the fact that most patches are observed during southward IMF [*Buchau and Reinisch*, 1991].

The problem then becomes one of understanding how the entry of flux tubes into the polar cap produces patches, rather than a continuous "tongue" of ionisation. The purpose of our paper was to point out that the new concepts of flow excitation developed by *Cowley and Lockwood* [1992] provide a natural solution to this problem if the dayside reconnection rate varies. Our mechanism does not require the day-night terminator to lie in a precise position close to the equatorward edge of the convection-dominated region. This is because it does not work by expanding the convection pattern equatorward, as envisaged by *Anderson et al.* and as assumed by REA. Instead, our mechanism is based on the more general idea that time-dependent reconnection and convection cause flux tube loci from widely varying regions (in MLT and latitude) to converge, giving steeper plasma density gradients on the edges of patches. Some misunderstanding has arisen from the simplified illustration we used in our figure 4, in which the only pre-existing density gradients outside the polar cap were envisaged as resulting from the solar zenith angle. In general, we would expect convection to give more complex structure which means the mechanism will operate under a much wider range of conditions than REA state.

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