

# PHYSICAL ORIGIN OF DIFFERENCES AMONG VARIOUS MEASURES OF SOLAR MERIDIONAL CIRCULATION

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## ABSTRACT

We show that systematic differences between surface Doppler and magnetic element tracking measures of solar meridional flow can be explained by the effects of surface turbulent magnetic diffusion. Feature-tracking speeds are lower than plasma speeds in low and mid-latitudes, because magnetic diffusion opposes poleward plasma flow in low-latitudes whereas it adds to plasma flow at high latitudes. Flux transport dynamo models must input plasma flow; the model-outputs yield estimates of the surface magnetic feature tracking speed. We demonstrate that the differences between plasma speed and magnetic pattern speed in a flux-transport dynamo are consistent with the observed difference between these speeds.

## 1. Introduction

Observational estimates of meridional flow in the photosphere have been made for many years using three principal methods. These include the tracking of surface features such as magnetic elements (Snodgrass & Dailey 1996; Hathaway & Rightmire 2010) and surface Doppler signal from supergranulations (Švanda, Klvaňa & Sobotka 2006; Švanda, Klvaňa, Sobotka & Bum 2008); Doppler shifts of selected spectral lines (Ulrich 1993; Ulrich & Boyden 2005); most recently Doppler shifts of acoustic frequencies detected by helioseismic instruments (Basu & Antia

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2010; Gizon, Birch & Spruit 2010). Each of these methods has different strengths and weaknesses that have been discussed extensively in the published literature. They also are measuring different quantities, so they should not necessarily give the same results. In particular, both Doppler-based methods should be measuring the flow of the plasma, but the tracking methods are sensing the movements of features in the plasma, not necessarily the plasma itself. By the laws of MHD, when magnetic diffusion is present, field lines and patterns can ‘slip’ relative to the plasma flow, since they are not ‘frozen in’.

On the Sun we are dealing with turbulent magnetic diffusion, caused by the time changes in supergranulation (Leighton 1964). Both surface transport models and flux-transport dynamo models solve equations that are in fact spatially and temporally averaged over the detailed structure of supergranules; therefore both contain turbulent diffusion, and in both models the “mean” field lines are not frozen in. There will also be magnetic diffusion on still smaller spatial scales, particularly within supergranules, but this effect should be isotropic (Švanda, Klvaňa & Sobotka 2006; Švanda, Klvaňa, Sobotka & Bumba 2008) and not contribute to a net transport of flux in latitude. Outside of the immediate neighborhood of active regions, the turbulent magnetic diffusivity should be nearly homogeneous (independent of latitude and longitude) but magnetic flux will be diffused in latitude and longitude because in general there will be gradients of flux in both latitude and longitude. It is the difference between pattern speeds and plasma flow that we focus on in this paper.

It is well known that the surface of the Sun has a highly structured magnetic field as well as turbulent motions. These turbulent motions will also move patterns of magnetic features, in addition to and in competition with the movement due to global flows such as differential rotation and meridional circulation. The tracking of magnetic features yields a ‘flow’ speed in latitude due to the combined effects of meridional circulation and turbulence, so this speed is bound to be different from that of the plasma flow. Is it possible to identify and measure this difference, and learn about physics of the Sun from it? What can flux transport dynamo models tell us about the difference between pattern speeds and plasma speeds? Can the output of flux-transport models estimate the turbulent diffusivity from the difference between pattern speed and plasma flow? We attempt to answer these questions in the following sections.

## 2. Observational evidence of differences

It is now possible to compare the measured meridional flow speeds from surface Doppler, helioseismic and magnetic pattern tracking methods for the whole of solar cycle 23. These measurements are displayed in Figure 1. The red curve is the surface Doppler results obtained

from the analysis of Mount Wilson Observatory data, already shown in Dikpati et al. (2010). The green curve is the helioseismic estimate from Basu & Antia (2010), and the blue curve is for magnetic pattern tracking reconstructed from the figure 3 of Hathaway & Rightmire (2010). Note that we omit the uncertainty bars in each of the curves, because our focus is on understanding the physical origin of one particular systematic difference between the magnetic feature tracking-speed and Doppler-based plasma-speed, rather than analyzing the accuracy of the methods. Also note that the time-variation in the meridional flow within each solar cycle primarily arises due to the inflows toward the active regions Zhao & Kosovichev (2004); Švanda, Kosovichev & Zhao (2007); Hindman, Haber & Toomre (2009). But we have considered in Figure 1 the meridional flows averaged over the entire cycle, because we are focusing here on understanding the systematic difference between magnetic feature tracking speed and Doppler-based plasma-speeds.

We see that for the latitudes where both are measured, the surface Doppler and helioseismic results are almost the same. Unfortunately helioseismic methods can not reach to as high a latitude as can surface Doppler. We see that the surface Doppler speed peaks around  $20^\circ$ , while the helioseismic results peak at  $30^\circ$ . Their peak amplitudes are within  $1 \text{ m s}^{-1}$  of each other. Both peaks are broad and it is not clear that there is any difference in either peak amplitude or latitude of the peak.

By contrast, the pattern tracking method yields a peak around  $50^\circ$  latitude, which is 25-30 % lower than the other peaks. The difference between tracking and the other velocities is significant at all latitudes equatorward of the peak. Poleward of its maximum, the differences are much smaller. A difference between tracking-speed and plasma flow-speed of magnitude  $5 \text{ m s}^{-1}$  in the latitude range from  $5^\circ$  up to about  $40^\circ$  magnitude have also been reported by Švanda, Kosovichev & Zhao (2007) and Švanda, Zhao & Kosovichev (2007).

By heuristic reasoning, we show in the next section that the differences between the pattern tracking and the other velocity measures are due to the effects of magnetic diffusion on the pattern tracking speed.

Surface Doppler and magnetic tracking measures of meridional flow also exist for cycle 22 (Dikpati et al. 2010; Ulrich 1993; Snodgrass & Dailey 1996; Latushko 1994; Cameron & Hopkins 1998). For that period too the surface Doppler velocity is larger than the pattern velocity peak and occurs at a lower latitude. In addition, the plasma flow from surface Doppler measurements reverses sign and becomes equatorward above about  $65^\circ$  latitude. This same behavior is seen in two tracking velocity profiles (Snodgrass & Dailey 1996; Latushko 1994). There too the reversed tracking velocity is smaller than the surface Doppler velocity. This result is also explained by the heuristic arguments we give below.

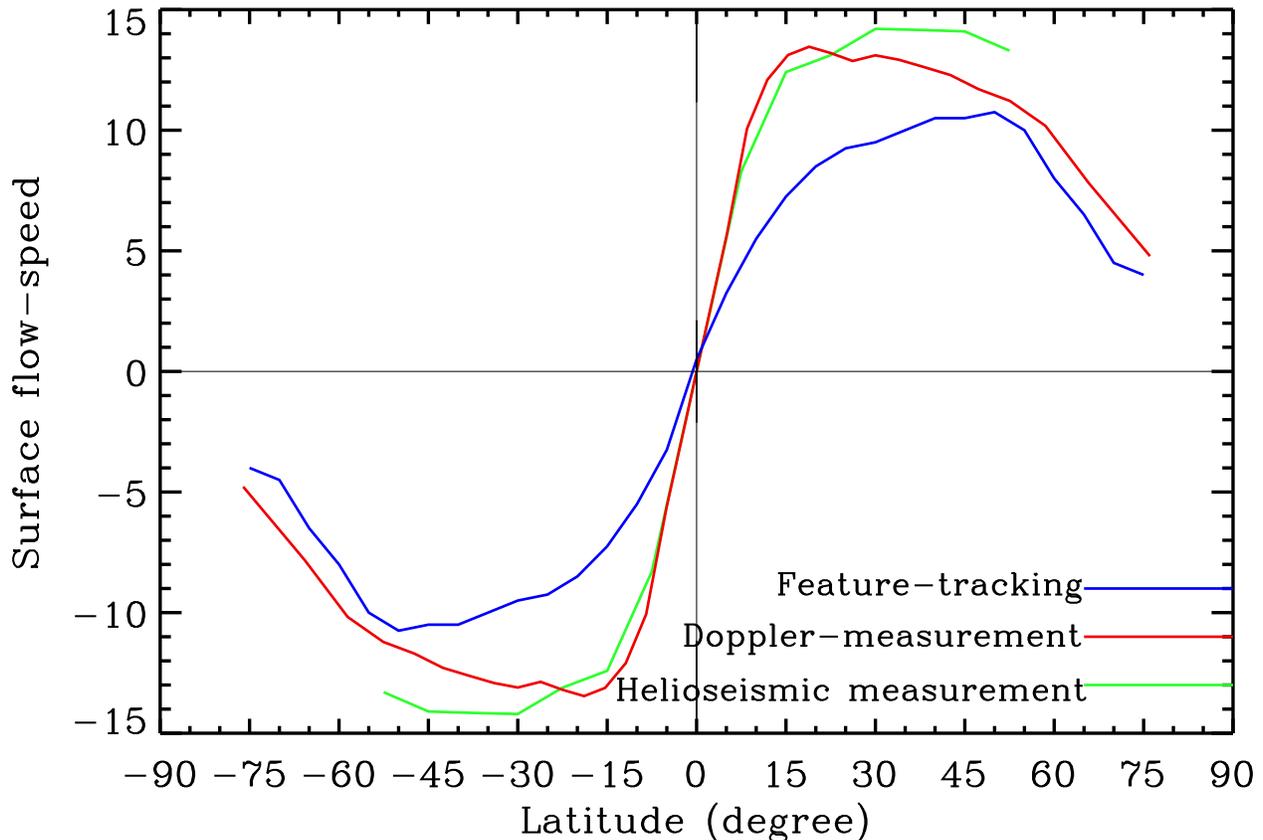


Fig. 1.— Surface meridional flow speeds from various measures for solar cycle 23 (averaged over the entire cycle). Red curve: surface Doppler speed from Mount Wilson Observatory; green curve: helioseismic measurement from Basu & Antia (2010); blue curve: magnetic feature movement read off of figure 3 of Hathaway & Rightmire (2010).

### 3. Heuristic explanation of differences in speed

Starting from the observations of meridional velocities summarized in the previous section, we give a heuristic physical explanation for the systematic differences between the surface Doppler and helioseismically determined values, and those associated with the movement of magnetic patterns. In schematic form, these differences are illustrated in Figure 2. The red curve denotes a predominantly poleward plasma velocity  $V_P$  that peaks in the range  $20^\circ - 30^\circ$  latitude. The blue curve shows the magnetic pattern velocity  $V_M$ . It has a lower peak amplitude compared to the plasma velocity and it peaks at a substantially higher latitude, between  $45^\circ$  and  $55^\circ$ . The systematic difference between the two velocities is that at low latitudes, the plasma velocity is faster, while at high latitudes the two velocities are about the same.

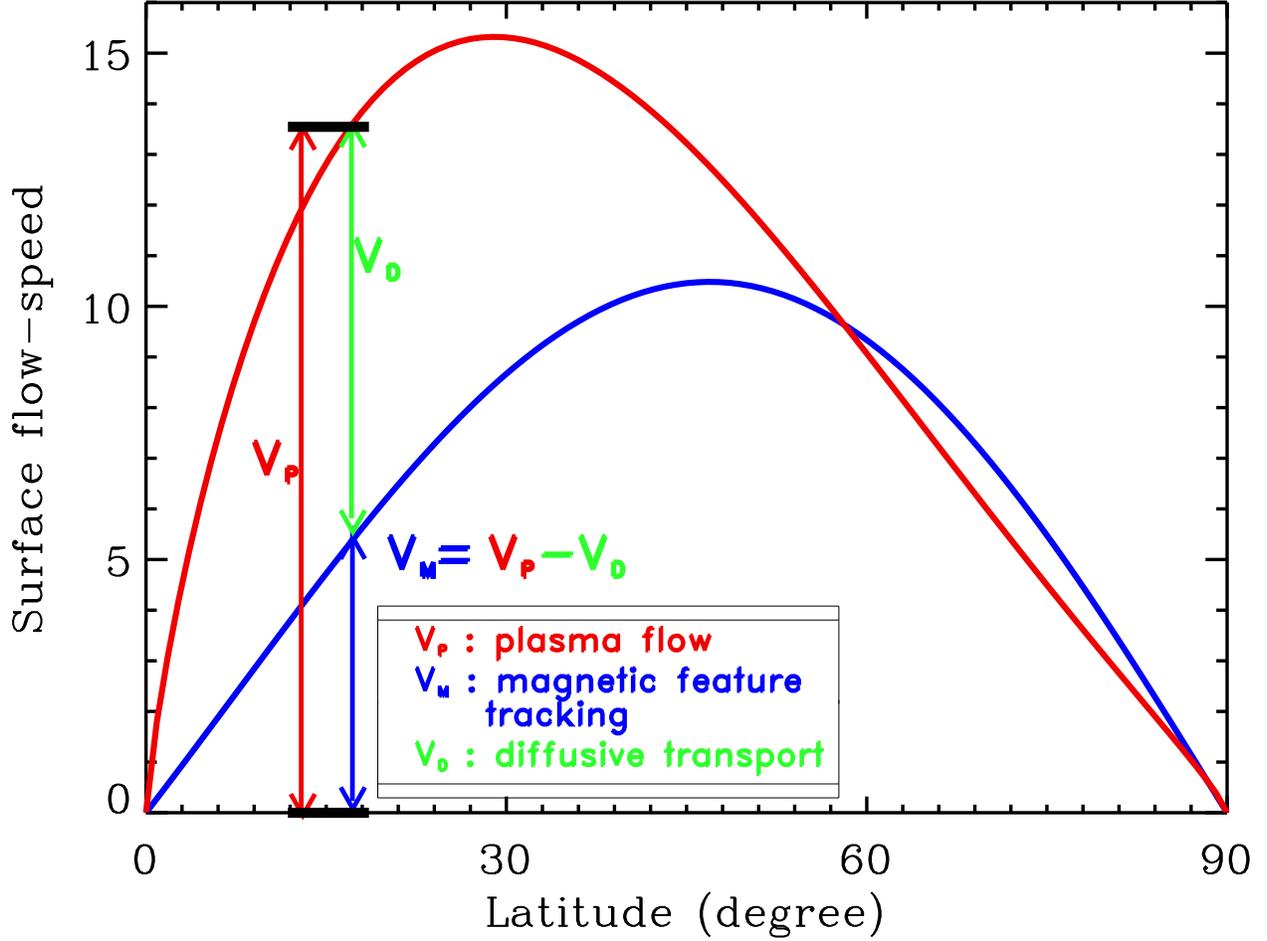


Fig. 2.— Schematic of plasma (red curve and symbols) and magnetic feature tracking (blue curve and symbols) speeds, with difference due to diffusion speed (green arrow and symbols).

These differences can be explained in terms of the turbulent magnetic diffusion. We can define a 'diffusion velocity'  $V_D$ , given by  $\eta/L$ , in which  $\eta$  is the turbulent diffusivity, typically taken to be  $2 - 8 \times 10^{12} \text{ cm s}^{-1}$  in the solar photosphere, produced by mixing by supergranulation, and  $L$  is a latitudinal length scale.  $L$  should be some fraction of the distance between equator and pole, a distance over which the longitudinally averaged surface radial field varies by a substantial amount. To illustrate the magnitude of this velocity, if we roughly take  $L = 10^{10} \text{ cm}$  (about 1/10th of the distance between equator and pole) we get  $V_D = 2 - 8 \text{ ms}^{-1}$ , values comparable to the plasma flow.

Since the surface source of large scale surface poloidal fields is due to the decay of emerged, tilted, bipolar active regions, the peak of the source and hence of the surface radial fields is almost always found at or near sunspot latitudes. In the absence of diffusion, these

surface poloidal fields would always be carried towards the poles by the poleward plasma flow. We should expect an asymmetric apparent outflow from activity latitudes, because the turbulent diffusion should increase the poleward transport rate in latitudes poleward of spot latitudes, and decrease that transport rate in low latitudes. This implies that the speed ( $V_M$ ) of magnetic features should be reduced in low latitudes, and increased poleward of sunspot latitudes. By this reasoning, in low latitudes we should have  $V_M = V_P - V_D$  while at high latitudes we should have  $V_M = V_P + V_D$ . To a first approximation,  $V_D$  represents the difference between the curves for  $V_P$  and  $V_M$ .

In the immediate vicinity of active regions ( $\sim 5^\circ$  latitude poleward and equatorward) there is an additional advective effect we have not included in the reasoning given above. This effect comes from the observation (Švanda, Kosovichev & Zhao 2007; Hindman, Haber & Toomre 2009) that there are persistent inflows of plasma from both poleward and equatorward sides of active regions. These flows would have the effect of reducing the apparent outflow of magnetic patterns. This feature is relatively localized, however, and in this first study we have not attempted to include it in the more global reasoning we are focusing on here. It must be included in more advanced models that examine in more detail the differences between plasma flow and magnetic feature tracking.

The observations in Figure 1 and the schematic in Figure 2 both show the substantial difference between plasma and magnetic feature tracking speeds occurs in low and mid latitudes, but not in high latitudes. This implies that the diffusive ‘speed’ must be low there. How is this possible? The concept of turbulent diffusion of magnetic elements across the solar surface due to the existence and evolution of supergranule patterns originated with Leighton (1964). In magnetic regions supergranules are distorted and difficult to distinguish from the magnetic features, because supergranules can be detected either in line-of-sight velocity or Ca-K maps, in which magnetic features are also seen (Švanda, Klvaňa & Sobotka 2009). Therefore, except in the immediate neighborhood of active regions, supergranule characteristics (horizontal scale, lifetime) are seen to be nearly independent of latitude and longitude. It follows that, for the diffusive speed to be much lower in high latitudes than low, the gradient of the surface radial field must be on average much lower there than equatorward of the peak in the poloidal source. The diffusive transport rate is given by  $\frac{\eta}{r} \frac{\partial B_r}{\partial \theta}$ . The diffusive speed associated with this transport is given by  $\eta/r\Delta\theta$ , where  $\Delta\theta$  is the difference in latitude over which the difference in radial fields is measured. The quantity  $L = r\Delta\theta$  is, therefore, our length scale.

We can explain the differences between the profiles of plasma flow and magnetic pattern tracking speeds by considering qualitatively the latitudinal locations of the strongest radial fields of both polarities at four different phases of a solar cycle, namely at cycle onset,

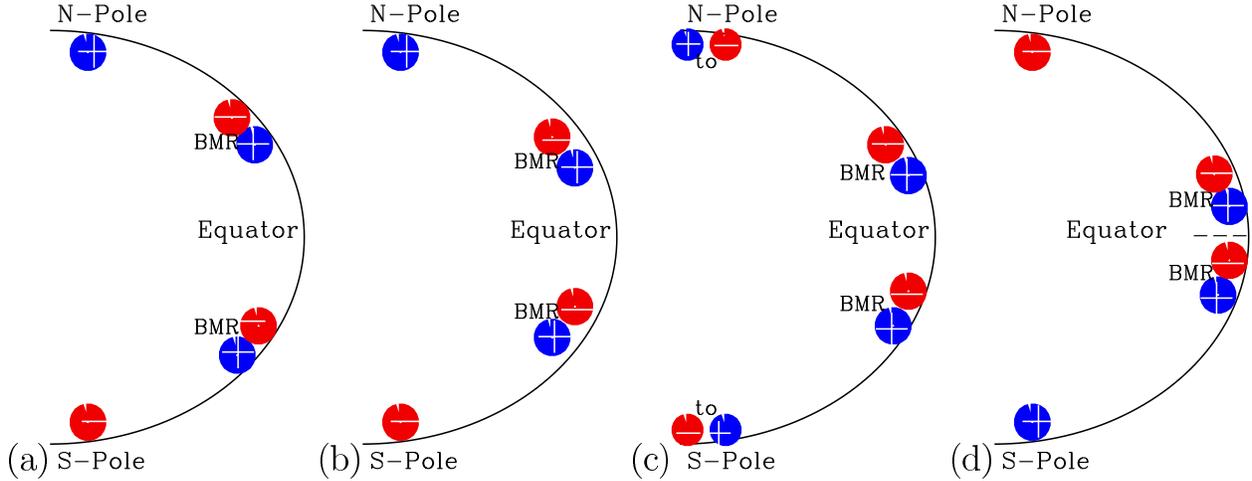


Fig. 3.— Schematic of latitude locations of peaks in radial field (positive peaks in blue, negative ones in red) for various sunspot cycle phases. a) cycle onset; b) ascending phase; c) maximum; d) descending phase. BMR stands for bipolar magnetic regions.

ascending phase, maximum, and descending phases (see Figure 3). At cycle onset (frame 3a), peak radial fields of opposite polarities are at the poles and at the location of the follower fields of sunspots; peak radial fields are also at the locations of the leading polarity spots in North and South hemispheres. In this phase of the cycle, the latitudinal distance between follower polarity spots and the pole of that hemisphere is about  $60^\circ$  in latitude. The distance between leader polarities in North and South hemispheres is also about  $60^\circ$ . So the latitudinal length scale for the evaluation of latitudinal gradients in radial fields is about the same in the two cases. Since polar fields are usually weaker than leading polarity fields in low latitude, the gradient of radial field is somewhat smaller between the follower fields and the pole of the same hemisphere than between the leader polarities in North and South hemispheres. Therefore even at this phase, the diffusive velocity toward the equator should be somewhat larger than that toward the poles above sunspot latitudes.

This difference gets bigger as the cycle progresses. During the ascending phase (frame 3b), the distance between the follower polarities and their respective poles increases, while the distance between leader polarities in North and South decreases. So the low latitude gradients in radial fields increase relative to the high latitude gradients, with a corresponding increase in the diffusive speed, as defined earlier, in low latitudes compared to high latitudes. This trend continues through the maximum (frame 3c) and descending (frame 3d) phases. Therefore the difference in gradients of radial field that drives the diffusive transport continues to increase. In addition, at maximum, the polarity of the radial fields at the poles switches to become the same as that of the follower spot polarity in that hemisphere, while

the polarities of leader spots in the two hemispheres remain opposite. This effect reduces the high latitude gradient relative to the low latitude gradient even more.

The net effect of these differences in gradient in radial fields, when averaged over a whole solar cycle, is to make the diffusive velocity directed toward the equator in low latitudes substantially larger than the diffusive velocity directed toward the poles at active-regions' latitudes and higher. Hence the magnetic pattern tracking velocity is substantially lower than the plasma flow in low and mid latitudes compared to that at high latitudes, as seen in Figures 1 and 2.

Some analyses of magnetic pattern data (Snodgrass & Dailey 1996) indicate the possibility of poleward movement between the equator and  $10^\circ$  latitude, and also equatorward movement poleward of about  $60^\circ$ . For simplicity, we have not included either of these feature in the schematic. In the case of the poleward low latitude movement, this could come about only if the turbulent diffusion were low enough, or the poleward plasma flow large enough. If this pattern persisted for a substantial fraction of a solar cycle, then during that cycle rather little radial magnetic flux would be annihilated at the equator.

Equatorward high latitude magnetic pattern movement could only come about if there is a second plasma meridional circulation cell there that is sufficiently strong to prevent flux from traveling all the way to the poles. If such a pattern persisted for most of a cycle, then the conveyor belt would carry flux down to the bottom near the interface of the two circulation cells rather than at the poles. This result is qualitatively consistent with the surface Doppler estimates of meridional flow by Ulrich & Boyden (2005), and could lead to a shorter solar cycle, as discussed in Dikpati et al. (2010).

#### 4. Pattern velocity from flux-transport dynamo solutions

In this section we investigate the latitudinal movement of magnetic patterns in a flux transport dynamo, running in a weakly non-linear kinematic regime. We simulate how a bipole source, inserted into the topmost layer (between  $0.97R$  and  $1R$ ) of the model, moves under the influence of a specified meridional flow single-cell as used in Dikpati et al. (2010) with a maximum flow-speed of  $15 \text{ m s}^{-1}$  and turbulent magnetic diffusion of value  $3 \times 10^{12} \text{ cm}^2 \text{ s}^{-1}$ . The bipole source is a Gaussian in the poloidal potential with full width at half maximum of  $6^\circ$ . This source results in 'leader' and 'follower' radial fields with Maxwellian profiles, each having full width at half maximum of  $3^\circ$  in latitude, with the Maxwellian 'tail' of the follower (leader) polarity fields extending toward the poles (equator). The source satisfies the condition that  $\nabla \cdot B = 0$ . We solve the induction equation in the axisymmetric

regime in two dimensional  $r - \theta$  plane and study the poleward transport of radial fields after they have been induced through the deposition of bipoles.

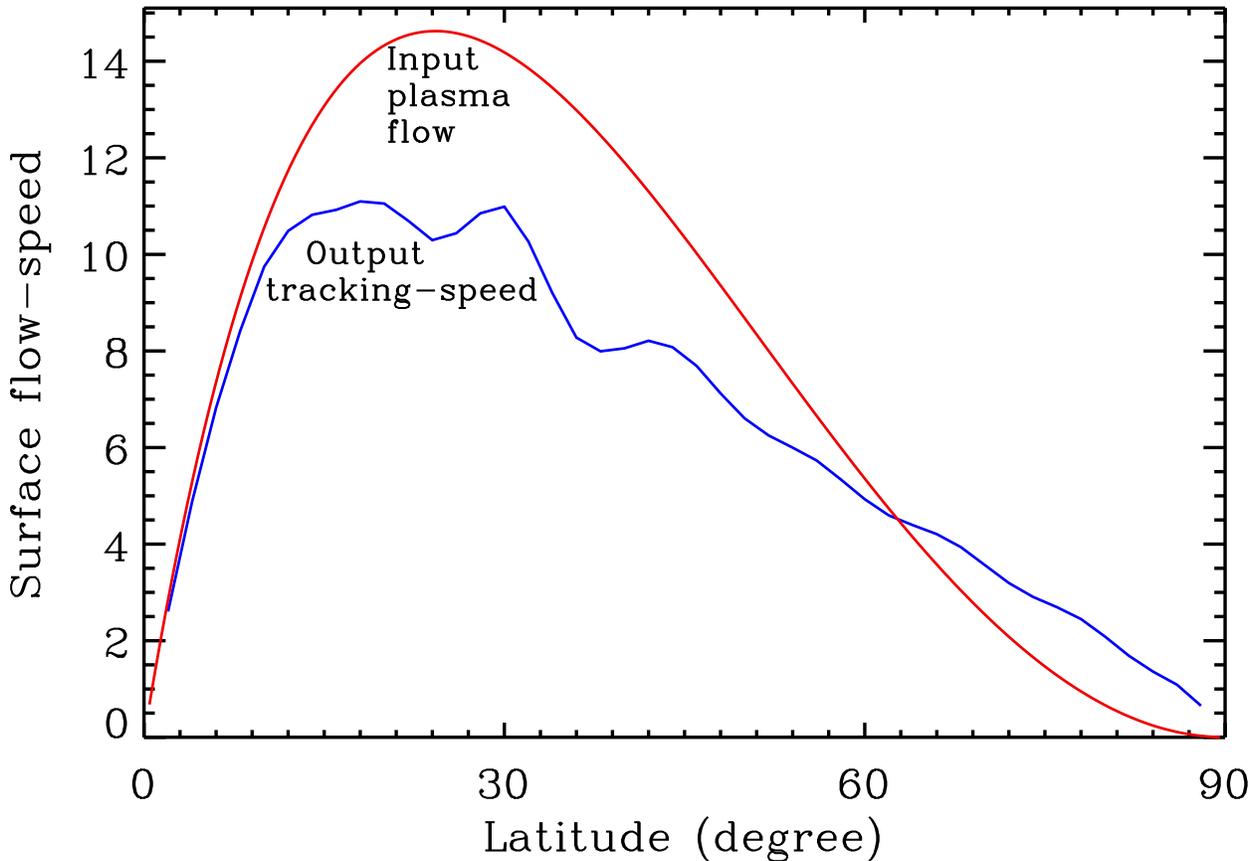


Fig. 4.— Comparison of surface plasma flow (red curve) used as input to flux transport dynamo, and simulation-produced magnetic pattern tracking speed (blue curve), derived from model-output.

We performed a series of numerical experiments in which the bipoles are induced into the model for a period of 12 days, after which this source is removed. All the physical processes in the model act on this source from time  $t=0$ . After removal of the source, the latitudinal position of a radial magnetic field contour of 30 Gauss of the follower polarity, which is on approximately the central part the Gaussian in radial fields, is tracked. From this tracking over a few weeks, a velocity is computed.

The experiments are performed on poloidal sources inserted every two degrees of latitude between  $2^\circ$  and  $88^\circ$  latitude, thereby generating a set of 44 velocities between equator and pole. These velocities are plotted (blue curve) in Figure 4, in which the plasma surface-flow speed that has been used as the input to the model is also plotted (red curve). The result

clearly shows that in low and mid-latitudes, the tracking speed is always lower than the plasma flow speed, by an amount that is similar to that observed. Only poleward of  $60^\circ$  latitude does the tracking speed exceed that of the plasma flow. That occurs where both speeds are low.

These experiments differ in some details from the heuristic description given in section 3, for example in the fact that in these experiments there are no polar fields to increase the magnitude of the high latitude gradients and diffusive velocities. Therefore we should expect to see the tracking velocity become larger than the plasma flow near the pole where plasma flow and diffusion velocity are always in the same direction. The simulations by Wang, Robbrecht & Sheeley (2009) using surface transport models with and without diffusion, showed that the slopes of the poleward surges were steeper when both flow and diffusion were included, than in the case when only flow was present (compare their figures 15 and 16).

Another important transport mechanism has not been considered in the present simulation, namely the turbulent pumping. The latitudinal component of the mean turbulent pumping as computed from the magnetoconvection simulations Ossendrijver, Stix, Brandenburg & Rüdiger (2002); Käpylä, Korpi, Ossendrijver & Stix (2006) is predominantly equatorward and peaks around  $15^\circ$  latitudes and with a magnitude of about  $1 \text{ ms}^{-1}$ . The influence of both the radial and latitudinal turbulent pumping have been studied in great detail by Guerrero & de Gouveia Dal Pino (2008). If such pumping is included in simulating the magnetic feature-tracking speed, even a larger difference between the input plasma speed and the model-derived tracking speed would occur at low latitudes. This might produce even better agreement between the model-derived tracking-speed and the observed values shown in Figure 1.

The result in Figure 4 confirms that in dynamo models the velocity from tracking of magnetic features should be considered as an output, not as a substitute for plasma flow speed which must be used as input to the model. In fact, about 25 years ago it was first shown by NRL scientists (Devore & Sheeley 1987; Wang, Nash & Sheeley 1989) that a meridional plasma flow peaking at low-latitudes around  $10^\circ$  from the equator is required to correctly explain the surface magnetic features' evolutionary properties. Schrijver & Liu (2008) also considered a variety of meridional flows peaking at different latitudes and showed that, to obtain the best-fit of observed polar field pattern of cycle 23 with their model-output, the flow must peak around  $15^\circ - 20^\circ$  latitudes. With much better techniques for measuring meridional flow, we now know that the plasma flow indeed does peak at low-latitudes (see red and green curves in Figure 1).

## 5. Concluding remarks

We have shown using heuristic reasoning and numerical simulations that the differences in surface meridional flow speed between the solar plasma and magnetic patterns can be explained as due to the effects of surface turbulent magnetic diffusion. All observational analysis referred to in this paper are done with valid methods. We repeat that the purpose of this paper was to understand the physical origin of the differences between tracking-speed and Doppler-based plasma speed. The plasma speed should be used as input into flux-transport dynamo models, whereas the observed magnetic pattern speed should be compared with the output of such models.

A very simplified case of a simulated feature-tracking speed derived from a flux-transport dynamo model-output has been presented here. It captures the physical origin of the differences between the plasma flow incorporated into the model and the tracking-speed derived from the evolving magnetic features in the model. However, there are many more aspects of the difference between plasma flow and magnetic pattern movement, which can be further explored using our model as well as other dynamo models benchmarked by Jouve et al (2008). Studies need to be done using models with higher magnetic diffusivity inside the convection zone (Yeates, Nandy & Mackay 2008), with the magnetic diffusivity quenched due to the presence of strong magnetic fields (Guerrero, Dikpati & de Gouveia Dal Pino 2009) and also with turbulent pumping included (Guerrero & de Gouveia Dal Pino 2008). Perhaps the importance of physical ingredients below the surface layer can be assessed by comparing model-derived tracking-speed from dynamo models with those obtained from surface-transport models (Wang, Robbrecht & Sheeley 2009; Schrijver & Liu 2008).

From the input of Doppler plasma flow in all such models, the comparison of model-derived tracking-speed with the observed tracking-speed could give new estimates of the turbulent diffusivity on the surface of the Sun. Other plasma flow profiles could also be used, including ones that allow for a second, reversed plasma meridional flow cell in high latitudes as used by Jouve & Brun (2007); Bonanno et al (2005); Dikpati et al. (2010) to see how strong such a flow must be to reverse the magnetic pattern movement, as found for cycle 22 by Snodgrass & Dailey (1996). Different representations of the bipole source could also be explored.

The simulation presented in §4 was performed in an idealized environment, namely without any background magnetic fields present in the Sun. Reality is more complex than that. For example, at high latitudes background polar fields are present with certain polarity and strength, and at sunspot latitudes the active regions' fields appear and disappear as function of solar cycle. A forthcoming paper will incorporate these complex background magnetic fields in the Sun in order to investigate further the differences between the input

plasma flow and the output tracking-speed.

All of the flux-transport dynamo models discussed above are axisymmetric and therefore only include the longitude-averaged meridional flow. Given the recent observations of strong inflow-cells around active regions (Švanda, Kosovichev & Zhao 2007; Hindman, Haber & Toomre 2009), which have not only latitude dependence but also longitude dependence, flux-transport dynamos need to be generalized to include longitudinal dependence in meridional flow.

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