ON THE SLOW SOLAR WIND

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Abstract. A theory for the origin of the slow solar wind is described. Recent papers have demonstrated that magnetic flux moves across coronal holes as a result of the interplay between the differential rotation of the photosphere and the non-radial expansion of the solar wind in more rigidly rotating coronal holes. This flux will be deposited at low latitudes and should reconnect with closed magnetic loops, thereby releasing material from the loops to form the slow solar wind. It is pointed out that this mechanism provides a natural explanation for the charge states of elements observed in the slow solar wind, and for the presence of the First-Ionization Potential, or FIP, effect in the slow wind and its absence in fast wind. Comments are also provided on the role that the ACE mission should have in understanding the slow solar wind.

1. Introduction

The purpose of this paper is to discuss a model for the origin of the slow solar wind – why it exists; how it fits into the larger scheme of coronal structure and evolution; and why it contains compositional differences distinct from fast solar wind. This subject is particularly appropriate for consideration by the ACE mission since ACE will observe primarily the slow wind. ACE will fly near the equatorial plane and at a time of increasing solar activity when high speed flows from the polar regions of the Sun do not readily extend to low latitudes. Moreover, ACE, as we shall discuss, may be uniquely able to make measurements of the slow solar wind which will reveal interesting aspects of the conditions and dynamics in the corona.

We begin by considering the overall picture of fast and slow solar wind in the heliosphere, at least near solar minimum, when the concepts for the overall structure are well developed. At high heliographic latitudes, the polar coronal holes give rise to a fast, $\sim$750 km s^{-1} flow, which is remarkably steady (e.g., Phillips et al., 1995). However, at low latitudes, surrounding the streamer belt, the flow is slower, $\sim$400 km s^{-1}, but also more variable in density and speed, and it exhibits pronounced compositional differences which suggest a different origin from the high speed flow.

The charge composition of the solar wind is frozen-in in the low corona and is thus a measure of coronal electron temperature. Figure 1 is taken from work by von Steiger (1994), who uses *Ulysses* data to show the relative abundance of iron charge states in the fast solar wind from coronal holes and in the slow wind. The solid curve is the equilibrium charge state for a coronal temperature of 1.26

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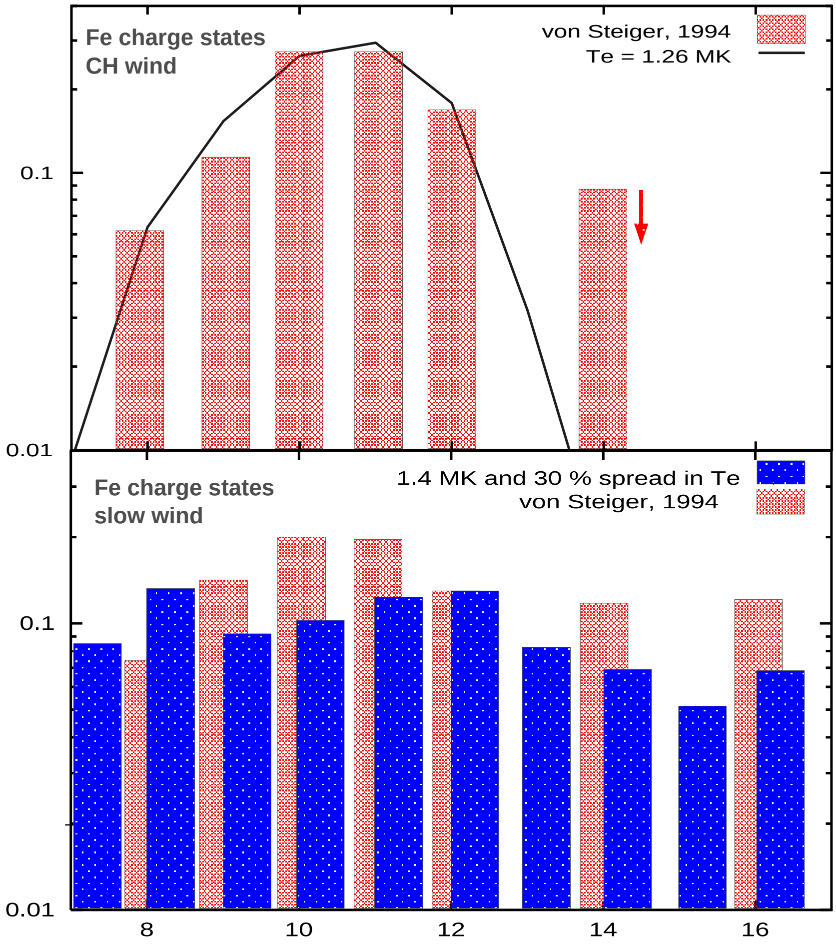

Figure 1. Comparison of charge states of Fe in the slow and coronal hole associated wind. A single uniform freezing-in temperature only applies in case of the fast wind. For slow wind, a temperature distribution of solar wind sources fits the data much better. Figure adapted from von Steiger (1994).

million deg. In the case of the fast wind, a single coronal temperature provides a reasonable fit to the data (note the charge state furthest to the right is an upper limit for the sum of charge states 13 and 14). Of course, looking at the charge states of different elements, which have different freeze-in points, can provide considerable information on the temperature profiles and other coronal parameters (e.g., Ko et al., 1997). However, to lowest order a single coronal temperature will suffice for the fast wind. In contrast, a single temperature will not provide a reasonable fit to the charge states observed in the slow wind. The distribution of charge states is simply too broad.

The second compositional difference between the fast and slow wind, and perhaps the most interesting, is the so-called First Ionization Potential, or FIP effect.

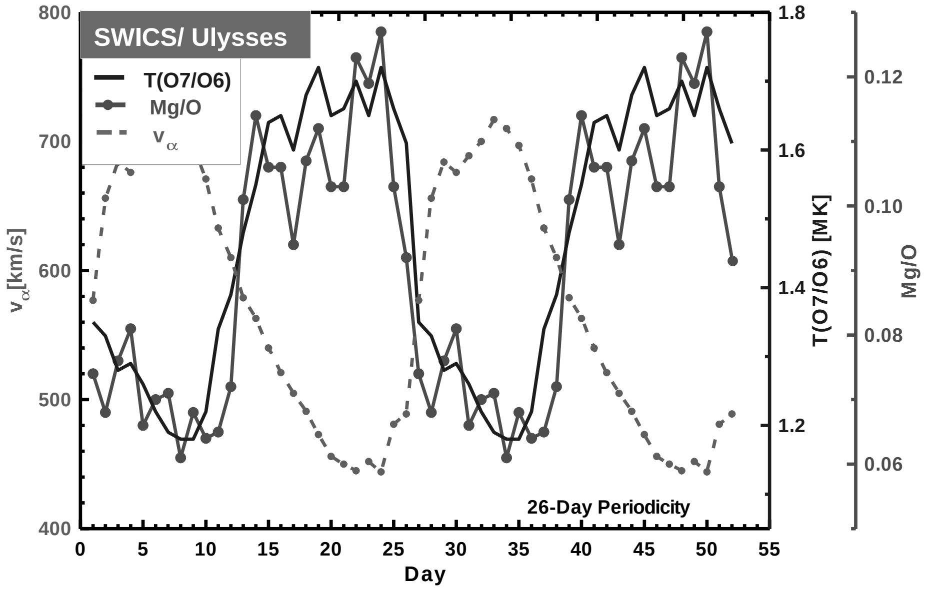

Figure 2. Superposed epoch analysis of *Ulysses* data showing the systematic variation in Mg/O ratio, the solar wind speed, and the coronal temperature inferred from the O^{7+}/O^{6+} ratio during the (effective) solar rotation period. The abrupt transition of freeze-in temperatures and composition indicate a different origin for fast and slow wind. Figure adapted from Geiss et al. (1995).

Figure 2 is from a paper by Geiss et al. (1995), again using *Ulysses* data. Shown here are the results of a superposed epoch analysis showing the solar wind speed, the freeze-in temperature for oxygen, as well as the magnesium to oxygen ratio. Magnesium is a low FIP element; it has a low first ionization potential and is easy to ionize. Clearly, magnesium is enhanced in the slow wind, and the transition is very abrupt, indicating a different origin for the fast and slow wind. When other elements are considered, a very general statement can be made: there is little evidence for a FIP effect in the fast wind, whereas, in the slow wind, there is a FIP effect by a factor of ∼4 (Geiss and Bochsler, 1985).

There are several theories which have been developed to explain the FIP effect (see, e.g., summary by Meyer, 1993). However, many have difficulty in explaining the presence of a FIP effect in the slow wind, and its absence in fast wind. Many of the theories assume a quasi-stationary chromospheric layer, with a particular geometry or temperature, which enhances the upward transport of low FIP elements into the corona. The difficulty, however, is that the chromosphere below coronal holes or closed field regions looks remarkably the same, suggesting that mechanisms which are strictly chromospheric should work equally well in fast and slow wind.

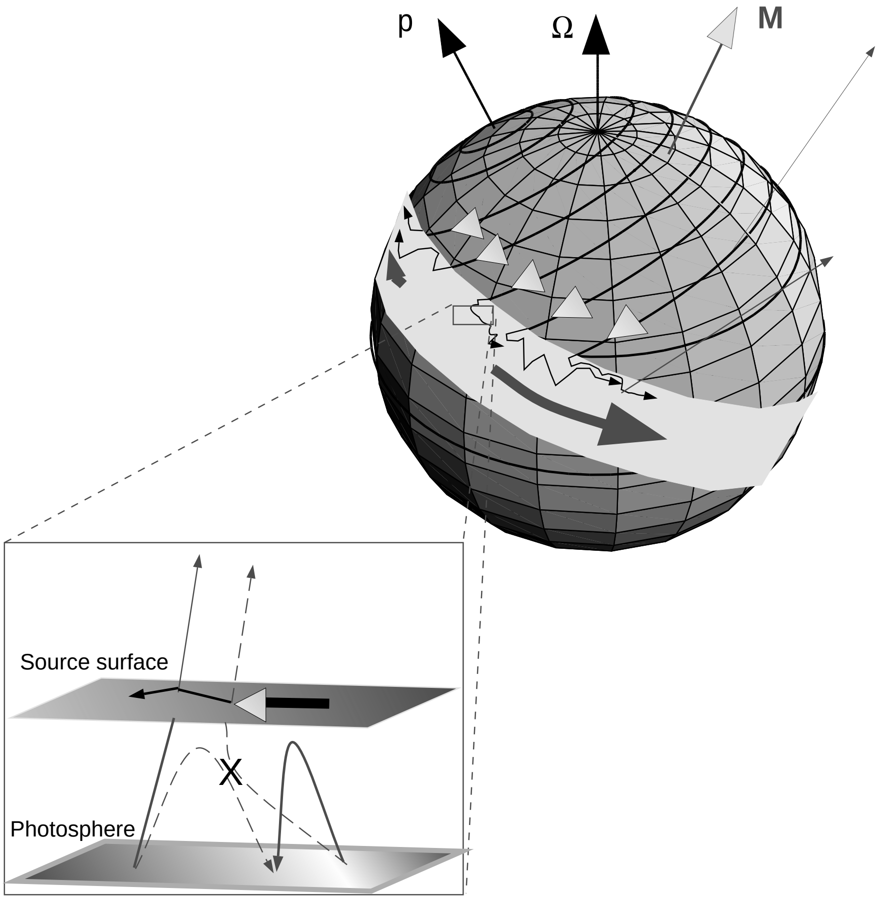

Figure 3. Reconnection scenario as described in text. Shown is the source surface of the solar wind in a frame co-rotating with the equatorial rotation rate. In open magnetic field regions, close to the pole, footpoints move in latitude. They are eventually convected into the band of closed magnetic fields at low latitudes. Due to subsurface reconnection events, a diffusive transport in longitude closes the footpoint curves on the solar wind source surface. For details refer to text.

2. A Theory

Consider a theory for the origin of the slow solar wind. This theory is a natural consequence of the new concept for the heliospheric magnetic field in fast solar wind which was proposed by Fisk (1996), viz., that the footpoints of the heliospheric magnetic field move extensively on the solar wind source surface as a result of the interplay between the differential rotation of the photosphere and the non-radial expansion of the magnetic field through coronal holes, which tend to rotate rigidly at the equatorial rotation rate. We review first this theory and its observational support, and then extend it to describe its consequences for the slow wind. The observational support is described in detail in Zurbuchen et al. (1997).

Consider a frame which co-rotates with the Sun at the equatorial rotation rate. The source surface of the solar wind – the surface beyond which the wind blows radially outward – is illustrated in Figure 3. The polar coronal hole is assumed to be centered on an axis ‘**M**’ which is offset from the rotation axis. The polar coronal hole, as does its lower latitude counterparts, is assumed to rotate rigidly at the equatorial rotation rate, i.e., the axis **M** is fixed in this frame. The expansion of the solar wind is taken to be non-radial from a limited region in the polar photosphere to a broader region on the source surface, and is symmetric about **M**. Consider, then, the field line which originates from the heliographic pole. It will penetrate the source surface at the location marked ‘**p**’. All other field lines, which are anchored in the differentially rotating photosphere, will execute trajectories on the source surface, which are some distorted circular patterns concentric about **p**, and in a direction indicated by the arrows. Clearly, the footpoints of heliospheric magnetic field lines on the source surface execute large excursions in latitude and longitude, which result in, in particular, large excursions in latitude of the heliospheric field. These excursions result in a direct magnetic connection from high to low latitudes which can account for the observation that particles accelerated in Co-Rotating Interaction Regions near the equatorial plane are observed at high latitudes (Fisk, 1996).

In Zurbuchen et al. (1997) observational evidence in support of this theory is presented. First, it is noted that there should be two characteristic frequencies for large-scale fluctuations in the field at high latitudes: 20 days and 34 days. The trajectories in Figure 3 are shown as smooth curves. In practice, the curves should be distorted, with variations in direction and in field magnitude, which move along the trajectories at essentially the differential rotation rate. It can readily be shown that at high latitudes, due to the offset of **p** from the rotation axis, *Ulysses* should observe disturbances on the footpoint trajectories twice, once as the footpoint trajectory crosses the latitude of *Ulysses* on one side of the Sun, and again on the opposite side. The time separation between these observations can be shown to be $\sim$20 days, i.e., a clear periodicity of 20 days in the field observations, which is quite unique to this theory, should be observed. At lower latitudes, where the footpoint trajectories tend to be more closely aligned with a single latitude, the periodicity should be $\sim$34 days, the differential rotation rate. This rate, however, may also be observed at higher latitudes, since the source surface is effectively a surface of constant pressure, and the effects of disturbances at lower latitudes may influence the magnetic field at higher latitudes as the pressure equalizes. Zurbuchen et al. (1997) analyzed magnetic field data from the southern solar pass of *Ulysses* and found that, in fact, two clear periodicities were observed, a strong signal at 20 days, and a somewhat weaker signal at 34 days. Zurbuchen et al. (1997) further analyzed the magnetic field directions seen in the heliosphere at high latitudes and found the clear sinusoidal pattern expected from the motion of the footpoints predicted in Figure 3.

There is clear observational evidence then that the footpoints of heliospheric magnetic field lines are indeed moving across the solar wind source surface. The obvious question to ask, then, is what happens when the field lines encounter low latitude regions, beyond the edge of the coronal holes, or equivalently, when the footpoints of the field lines in the photosphere encounter the coronal hole boundary. Clearly, Maxwell's equations must be satisfied, the divergence of the magnetic field vector must be zero, and the field lines must be continuous. Flux is then being deposited on one side of the Sun at low latitudes, the side where the arrows in Figure 3 are downward in latitude, and depleted on the opposite side. Such a deposition cannot increase indefinitely, and there must be transport of the field through the equatorial region from the side of deposition to the side of depletion, and a steady state achieved. A natural mechanism for such transport is reconnection, as is illustrated conceptually in Figure 3. Underlying the source surface at low latitudes are closed field loops. The field lines can encounter the sides of loops with opposite polarity, reconnect, and by doing so jump from location to location on the Sun, and effectively diffuse around the source surface near the equatorial plane to the opposite side of the Sun. For details concerning this magnetic field transport and reconnection scenario refer to Fisk et al. (1998).

This explanation for the transport of field lines in the solar equatorial region offers an explanation for one of the more puzzling magnetic field observations in the solar wind. There are intervals, sometimes extended, when the magnetic field is observed to be effectively radial near the equatorial plane, despite the strong tendency for the rotation of the Sun to yield a field with a strong azimuthal component. Footpoints diffusing around the Sun near the solar equator, in the direction opposite to that of the solar rotation, will have a reduced azimuthal component and, if the diffusion is sufficient fast, will be effectively radial.

This model for the behavior of the magnetic field at the Sun demands, then, that there are two distinct regions of the solar wind. In coronal holes, the wind is emitted along continuously open magnetic field lines, presumably yielding the fast steady wind. At lower latitudes, however, the field lines, as a result of their reconnection process, are continuously opening the tops of what had been closed loops, and allowing the material to flow outward into the heliosphere. The emission of the slow solar wind is then a sporadic process, dynamically driven when open field lines reconnect with previously closed loops. Such a sporadic origin for the slow wind is not a new concept; however, the driving mechanism, indeed the inevitability of such a process that results from footpoint motions in coronal holes, perhaps is.

Consider then the observations of charge states shown in Figure 1. Coronal loops, of course, have many different sizes, configurations, and particularly temperature. If we assume that the slow solar wind results from the superposition of material from many different loops, the resulting charge states in the observed wind will similarly reflect this spread in temperature. In the darker bars in Figure 1, plotted against the observations of iron charge states in the slow wind, we assume that there is a Gaussian distribution in temperatures, with a 30% spread about a mean temperature of 1.4 MK. Clearly, the fit to the data is much better than that from a single coronal temperature.

Consider also the FIP effect that is observed in the slow solar wind, but which is far less pronounced in the fast wind. Clearly, the obvious mechanism is to take advantage of the loops. Fast wind from coronal holes expands continuously outward; slow wind accumulates in closed loops for hours to days, and then is released into the heliosphere. There are several options here, but one simple mechanism, as is discussed in detail in Schwadron et al. (1998), is to consider the process by which loops are heated. Elements in the corona do not appear to be heated to a uniform temperature, but rather the heating appears to result more in a constant thermal speed, as is frequently observed in the solar wind, at least in regions where the coronal density is not sufficiently high to demand collisional dominance. Such heating will occur, presumably, by the interaction of the ions with MHD turbulence.

Assume, then, that such heating occurs in the larger loops of the corona, which extend to high altitudes and are therefore more likely to open to form the slow solar wind. Assume also that this heating extends downward into the transition layer, where particles are partly ionized. Clearly, it is essential to have the characteristic time for wave heating to be less than the ion collision time, which tends to yield a constant temperature for all ions. As is discussed in Schwadron et al. (1998) such a situation is possible even down into the transition layer. Ions will maintain a high temperature, or equivalently a large scale height throughout the loop. Particles that are neutral will not experience the heating due to MHD turbulence and will have a smaller scale height. Thus, species which are easily ionized – the low FIP elements – will on average have a large scale height throughout the loop. In contrast, the low FIP elements on average will have a smaller scale height at the bottom of the loop. At the top of the loop, then, the density of low-FIP elements is intrinsically larger than that of the high-FIP elements.

This mechanism for producing the FIP effect can be described by a simple set of equations. As is discussed in detail in Schwadron et al. (1998), we assume the loop contains a fixed number of particles with photospheric abundance. The minor ions in the loop, heavier than helium, are heated by waves to a constant thermal speed; hydrogen ions are not heated by waves, and have the usual steep temperature profile between the chromosphere and the corona; and neutrals retain the temperature profile of the hydrogen. The ionization state at the bottom of the loop is determined by both collisional ionization, and by the solar UV and EUV flux. The gas is then assumed to be in hydrostatic equilibrium. The relative composition at the top of the loop, which is placed at 100 000 km, is shown in Figure 4. The predicted ratio of the abundance of a species relative to oxygen, divided by the same ratio in the photosphere, is shown as an open bullet symbol. The error bars indicate qualitatively the natural spread of measurements due to changes in the wave-field (for details refer to Schwadron et al. (1998)). The squared black and white bars are the observations in the fast wind, where there is little or no FIP

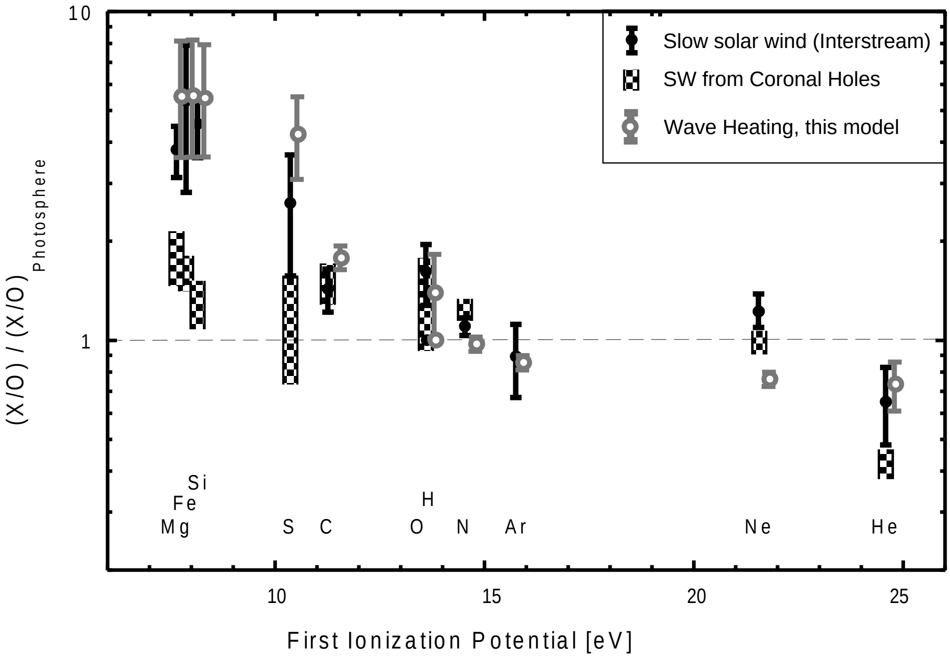

Figure 4. Solar wind abundance ratios, relative to their photospheric values, as a function of the first ionization potential. The measurements are compared with results from a FIP fractionation model described in the text. Figure adapted from von Steiger (1994).

effect. The full symbols with error bars are the observed abundances in the slow wind. Clearly, there is reasonably good agreement for all elements.

Notice, that in order to explain the observed helium abundance, an intermediate heating rate (between heavy ions and protons) has to be assumed. This seems to contradict *in situ* observations of the kinetic properties of solar wind ions, which indicate that helium responds to wave-particle interactions very much in a way similar to heavy ions. However, deep in the corona, wave heating of helium could be less effective than for the minor ions since helium can be a more major constituent of the plasma, with sufficient mass density to effect the properties of the waves.

Finally, we should ask why the wind which is released sporadically from loops is slower. There is no immediate answer here, and further numerical modeling will be required. It may be that the initial density is higher, with a lower final speed resulting. It may be the result of the sudden, almost adiabatic expansion from the previously closed loop, in contrast to the continuous deposition of energy in the steady solar wind.

3. Implications for the ACE Mission

Consider, then, what the solar wind composition instruments SWICS and SWIMS on ACE (Gloeckler et al., 1998) can do to provide information on the origin of the slow solar wind. All of the calculations shown in Figure 1 were averaged over many loops, in part, because the observations with which they were compared were accumulated for hours to days, to acquire sufficient statistics. ACE, however, is in a position to obtain good statistics on shorter time scales. Unlike *Ulysses* which observed the slow solar wind primarily en route to Jupiter, where the density is reduced by the square of the distance, ACE remains at 1 AU and should be able to observe material with sufficient statistics on the scale of $\sim$1 hr. On this time scale the material may originate from a single loop, although we cannot be sure that there is not considerable mixing near the Sun. We may discover that observing on this limited time scale reveals that the observed charge states of the slow solar wind are consistent with a single temperature, characteristic of one loop. Comparing observations from many different time intervals will reveal the variations in the temperatures and conditions in the corona which give rise to the slow wind. Similarly, on a scale of less than 1 hr we should expect considerable variation in the FIP effect in the slow wind, which results from the variations in the wave heating, the altitude where this heating begins, and/or the lifetime of the loops, prior to their being opened to form the slow solar wind.

4. Concluding Remarks

We should remember that the theory described here applies only in the years around solar minimum, when there are well-developed polar coronal holes, across which the field lines move. It is not clear how this mechanism will apply near solar maximum. There are certainly coronal holes on the Sun nearer to solar maximum, but they are short lived, and the concept of field line motion across them, with resulting reconnection in closed loops, may be quite different.

Acknowledgements

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