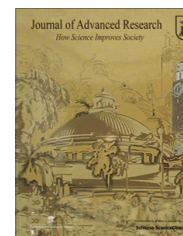




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**REVIEW**

Sources of solar wind over the solar activity cycle

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Abstract Fast solar wind has been recognized, about 40 years ago, to originate in polar coronal holes (CHs), that, since then, have been identified with sources of recurrent high speed wind streams. As of today, however, there is no general consensus about whether there are, within CHs, preferential locations where the solar wind is accelerated. Knowledge of slow wind sources is far from complete as well. Slow wind observed in situ can be traced back to its solar source by backward extrapolation of magnetic fields whose field lines are streamlines of the outflowing plasma. However, this technique often has not the necessary precision for an indisputable identification of the region where wind originates. As the Sun progresses through its activity cycle, different wind sources prevail and contribute to filling the heliosphere. Our present knowledge of different wind sources is here summarized. Also, a Section addresses the problem of wind acceleration in the low corona, as inferred from an analysis of UV data, and illustrates changes between fast and slow wind profiles and possible signatures of changes along the solar cycle. A brief reference to recent work about the deep roots of solar wind and their changes over different solar cycles concludes the review.

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Introduction

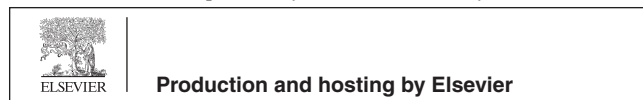
The search for solar wind sources dates back to about 1950 – with early insights from the end of the previous century – and got further motivation from Parker's theoretical work [1]. The shape of the solar minimum corona, which had been known for years via eclipse observations, is highly suggestive of a magnetic field configuration where open field lines are rooted in polar regions where, as a consequence, solar wind might

originate. The solar maximum corona, with its variety of structures, is much more confusing and is not clearly hinting to any region as source of solar wind. We have two capabilities to study solar wind, one arising from direct wind observations by in situ instrumentation, the other arising from remote sensing of the solar corona: establishing a link between the two views is crucial in identifying the wind source regions, but is very difficult to locate precisely the area from which wind emerges via, for instance, backward extrapolation of field lines. Clearly, as the Sun progresses through its solar activity cycle and polar coronal holes withdraw to small areas around the poles, more wind emanates from regions outside holes, as nicely shown by *Ulysses* observations [2], and we need to combine remote and in situ data to provide a comprehensive view of the Sun over the activity cycle. The earliest information about changes of the wind over the years came through scintil-

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lation measurements [3], whose role, not always recognized, will be further illustrated in the next Section. This review initiates with a brief historical overview of the first studies in slow and fast wind and then proceeds to later results, acknowledging the role that space missions, like *Ulysses* and *SOHO*, have played in this field. Different sources of slow wind are briefly illustrated but the discussion is limited to the two traditional states of solar wind, fast and slow, and does not cover at all the wind associated to coronal mass ejections (CMEs), some times considered as a further wind type. A relevant issue, often not covered in solar wind reviews, to which here some space is dedicated, concerns the difference between fast and slow wind acceleration in the low corona. The wind acceleration profile is hardly known and only recently novel diagnostic techniques have allowed us to infer, from a spectroscopic analysis of remotely acquired UV data, the profile of the solar wind speed vs. heliocentric distance over the first few solar radii, providing theoreticians with a further constraint to their models. These “observed” profiles show that the wind acceleration process has different characteristics in slow and fast wind. The topic of the deep roots of solar wind will be discussed at the end of the paper, where a (non exhaustive) list of open issues that need to be answered before we reach a thorough knowledge of wind properties is also given.

A brief historical overview of the search for solar wind sources

Back in 1720–1740, when we obviously did not know about solar wind, we nevertheless had some information about a wind-related phenomenon, geomagnetic storms. And we did know, at the time, that the geomagnetic field exhibits a strong variability and that aurorae are accompanied by geomagnetic disturbances. Still, we have to wait a century before the start of solar-terrestrial physics, which we may date back to when the sunspot cycle was discovered by Schwabe. And we need to wait 50 years more to find the prophetic words of Maunder who hypothesized that the “Earth has encountered. . . a stream, which, continually supplied from one and the same area of the Sun’s surface, appeared to us, at our distance, to be rotating with the same speed as the area from which it rises”. Maunder even gave the approximate size of the stream diameter, that he estimated to be about 20° wide. His insight had to wait about 70 years before it could be proven true by the identification of the mysterious M regions – introduced by Bartels in the thirties [4] – with coronal holes.

This result was achieved in 1973 by Krieger, Timothy and Roelof who followed in the steps of Maunder by pointing out the striking agreement between the Carrington longitude of the solar source of a recurrent high velocity stream and the position of a coronal hole [5]. We were in the Skylab era and the time was ripe for such an achievement as, in those years, *Pioneer 6* and *7* and *Vela*, had helped establishing the connection between recurrent open magnetic field and the stream recurrence, while, on the theoretical side, Parker’s work had made outflows a necessary component of the solar atmosphere and CHs had been singled out as favored wind sources [1–6,7].

Of course knowledge of the solar wind in the years 1975–1980 was mostly restricted to the plane of ecliptic: still, from studies of the wind speed over several years Sheeley and co-authors pointed out that the wind speed was lower at (near)maximum than at the time of (near)minimum (e.g. [8]).

Putting together data from *Vela* and *IMP* satellites it was concluded that the characteristic state of the solar wind was the high speed flow, that was at times modulated by the intrusion of low speed plasma [9]. Information about the wind properties as a function of latitude had been obtained from scintillation measurements: these led to the conclusion that the average flow speed varies with latitude, increasing with an average gradient of 2 km/s/deg towards the pole. The scintillation technique is based on the scattering of radio waves from a compact source by electron density irregularities in the solar wind [10] and, at the time, it was the only means that had the capability of sampling wind from high latitudes and hence point out the bimodal structure of the solar wind speed [11], beautifully confirmed by the in situ observations of the Helios probes [12].

The overall view of solar wind origin that was reached in the 1980s, although qualitative and lacking all the variety of slow wind sources later identified, was basically correct. We may conclude that, ~30 years ago, we knew that fast wind emanates from CHs, that it is steady, but that it possibly changes its speed with solar cycle. The question of preferential locations, if any, within the holes, from which wind might emerge, was not asked. Nor we had any information about the behavior of the solar wind close to the Sun, where it gets accelerated. Besides, information on slow wind sources, on slow wind acceleration, on its latitudinal behavior and on the solar cycle variation of wind properties were severely missing.

Space missions in the 1990–2000 decade

The 1990–2000 decade saw the launch of three space missions that turned out to be crucial for advancing our knowledge of solar wind properties: *Ulysses*, launched in October 1990, provided us with an in situ view of the wind behavior at different latitudes, while through the data that *SOHO*, launched in December 1995, acquired in the low corona, we got invaluable information on the solar wind acceleration. *ACE*, launched in April 1997, provided further information on the corona and wind elemental composition, that, as we will see, may be crucial for identifying wind sources as well as to understand the wind acceleration mechanism.

During its long lifetime, *Ulysses* made three polar passes (over both poles) sampling the latitudinal structure of the solar wind around solar minimum of cycle 22 (first orbit), around solar maximum of cycle 23 (second orbit) and, in its third orbit, once more around solar minimum (cycle 23). From these observations we learned that the simple bimodal structure at the minimum of cycle 22, where the fast, relatively homogeneous, solar wind from the poles gives way, around the solar equator, to a slower, denser and highly variable wind can change from one to the next minimum: in cycle 23 the fast wind, for instance, was slightly less dense (by 17%), slower (3%), and had a 20% less dynamic pressure than previously measured [13]. It is beyond the aim of the present review to discuss the origin of these changes, most probably related to the lower field strength in polar areas, but it is worth noticing that the wind changes not only with the solar cycle but also over different cycles. Examining now the structure of the wind at the time of maximum in the solar cycle we realize that the complex heliolatitudinal wind structure mimics the complexity of the solar activity structures that, as the solar cycle progresses,

appear at increasingly high latitudes. It looks reasonable to assume that diverse flows progressively contribute to solar wind originating from streamers, pseudostreamers, active regions, small holes and CMEs. Before examining how these sources contribute to the slow wind, we need to answer a question: how do we identify the origin of the wind observed in situ? In the next Section we describe the techniques by which this problem is solved.

Establishing an association between solar wind speed and wind source regions

Two techniques are usually adopted to connect wind streams observed in situ to their source on the Sun.

The one we illustrate first is based on the behavior of magnetic flux tubes: if we define an expansion factor, f_{ss} , as the factor by which a coronal flux tube expands between its base and the coronal source surface (i.e. the surface, whose radius is traditionally set at 2.5 solar radii, above which the field is radial), that is, if $f_{ss} = (R_{sun}/R_{ss})^2 B_0/B_{ss}$, then it turns out that the solar wind speed is inversely correlated with f_{ss} ([14–17]). This inverse relationship allowed Wang and Sheeley to account for wind sources over 22 years of observations [18]. Wang and Sheeley calculated the expansion factors via a potential field extrapolation: more recently, their original procedure has been modified by, e.g., Riley et al. who calculated the expansion factors via MHD models, or extended by, e.g., Kojima et al. who claim that the best indicator of the terminal wind speed is a combination of the expansion factor and the radial magnetic field strength at the photosphere [19,20]. This technique meets undoubtedly with success, in its original and/or successively modified version (e.g. [21]). However, there are difficulties: mapping wind streams back to the Sun implies extrapolating from 1 AU to the solar surface, ignoring, for instance, the interactions between slow and fast wind streams that introduce large uncertainties in the wind source location.

The other method by which we can identify the wind source regions, starting from in situ data, is based on the comparison between elemental abundance at the Sun and in the solar wind. It is well known that coronal abundances take different values in different structures and that abundances in fast wind and slow wind are different (e.g. [22]). Hence, *a priori*, it looks easy to compare abundances and connect wind streams to the areas where they originate. However coronal abundances show such a large variability even for the same kind of structures that is some times difficult to get clear results.

Let us now see how, and why, and which solar activity structures contribute to the slow wind.

Slow wind sources

Streamers have long been reputed to be sources of slow wind, although it has never been clear where exactly outflows might originate. Because streamers are closed loop structures that open up at their cusp, it might be predicted that some plasma escapes from streamers' tips. Indeed, White Light (WL) coronagraphs images showed blobs flowing outwards along streamers stalks. Assuming that blobs are tracers of slow wind and hence that they move at its speed, it has been suggested, by examining their outward trajectories, that slow wind originates from about 3 to 4 solar radii and increases its speed out to about 25 solar

radii where it reaches ~ 300 km/s [23]. But, does slow wind originate within the streamer core or does it flow along the boundaries of the streamers, or does it originate in the streamers' stalks? *SOHO/UVCS* spectrograph has shown that often streamers have, when seen in the OVI ion emission, a low emitting core, that suggests oxygen to be highly depleted there. This, and the WL observations, lead to different scenarios.

The configuration of a streamer, in its inner core, is not well known and it may be constituted by magnetically closed substructures intermixed with open fieldlines. Slow wind might flow along these open lines yielding the UVCS observed depletion in heavy ion emission [24]. Alternatively, magnetic reconnection between the highly stretched fieldlines in the streamers' stalks may result in the formation of plasmoids, observed as blobs. Magnetic reconnection is also likely to occur between the outer closed fieldlines at the streamer boundaries and the adjacent open flux, leading to flows along the newly created open field [25]. Also, sort of a streamer "evaporation" may occur when magnetic pressure is high enough to overcome magnetic tension stretching fieldlines to infinity and creating new open flux.

A final conclusion on the scenario best representative of the slow wind streamer contribution has not been reached, yet: most probably, streamer wind cannot be ascribed to a unique scenario.

Recently, a coronal structure quite similar, on coronagraph images, to streamers has been identified and revealed to be of a different nature [26]. This new configuration, dubbed pseudostreamer, originates in unipolar areas, in between coronal holes of the same polarity. Because pseudostreamers are rooted in unipolar areas, no current sheet is embedded in their stalks, which rules out the wind production mechanism that invoked reconnection within the stalk of the structure. Still, by analyzing *ACE* data, it has been inferred that pseudostreamers are sources of slow wind, although the mechanism by which wind originates has not been clearly ascertained [27].

That active regions (ARs) might contribute to solar wind was pointed out years ago from an analysis of interplanetary scintillation data [28], but the advent of the *Hinode* mission led to a proliferation of studies on this issue. Outflows at ARs edges are recognized to be associated with wind streams observed in situ because flows and streams have the same abundances [29]; however, it is quite difficult to make a connection and most of the present analyses focus on the detection of flows from peripheral areas of the ARs and on their properties. Intermittent and continuous flows have both been observed and is not clear whether the AR contribution to the slow wind is persistent or sporadic (e.g. [30,31]). Also, at times, outflows do not appear to reach a high enough speed to escape outwards (e.g. [32]). As to what precisely gives rise to outflows, the lateral expansion of active regions has been indicated, among others, as an adequate mechanism for accelerating plasma [33]. It is interesting to notice that, according to Sakao et al., ARs may contribute $\sim 1/4$ of the total mass loss rate of the wind [30].

We conclude this summary of slow wind contributors with low latitude coronal holes. Wind from these small holes has been recognized to be slower than wind from large polar holes, in agreement with prediction for the inverse relationship between expansion factors and wind speed. This (slow) wind source is the most obvious, among those cited above and we will not discuss it any further. Also, we will not deal with CH boundaries, that may be privileged sources of slow wind,

because of space limits: here it will suffice what we mentioned about the streamer-ambient boundary. Let us now revert to fast wind from polar holes and ask whether it preferentially originates in some precise locations within holes or whether the CH area uniformly contributes to fast wind emission.

Fast wind sources

We do not know, yet, whether the whole area of coronal holes evenly contributes to solar wind emission or whether there are sites within CHs that are preferential wind sources. Apart from more exotic and rarely occurring features, these might be bright points, plumes and transient X-ray jets. Bright Points (BPs), which may be considered as mini active regions, are easily seen in X-ray images of CHs and raised the interest of the community because a rough calculation of the number of particles, per unit area and per second, they may supply to the solar wind, assuming standard areal coverage and densities, and an outflow of 10 km/s, showed them capable of providing for the flux observed at 1 AU ($2 \times 10^8 \text{ cm}^{-2} \text{ s}^{-1}$) [34]. Moreover, the BP number appeared to increase at sunspot minimum, as if BPs were anti-correlated with the sunspot cycle, thus providing further, although indirect, evidence that they might be responsible for the solar wind. However, changes in CH BP number density vs. changes in the CH mass flux have been further analyzed and no correlation was found [35]; also, the density of BPs, when taking into account the variation of the background corona, turned out to be independent of the solar cycle [36]. Recently, works on *Hinode* and *TRACE* data found evidence for unresolved structures in BPs [37]. Taking this new information into account, a crude estimate of the BP lifetime, should they release their entire mass content to the solar wind and provide for its mass flux, yields a value of ~ 100 s, that is irreconcilable with the BP observed duration of a few hours. Hence, BPs have been ruled out as significant contributors to the solar wind.

The role of plumes, as sites where wind originates, is more subtle. In the past, different views have been proposed, on the ground of both observations and theory [38–40]. Locating plumes in the distant solar wind might unequivocally demonstrate their role, but their identification has not been possible: although different wind features, like pressure-balanced structures, microstreams and switchbacks have been proposed as in situ signatures of plume remnants, no definite association with coronal plasma has been established. The reader may refer to Wilhelm et al. for a comprehensive review of the present status of knowledge of plumes [41].

Transient phenomena closely related to plumes are X-ray jets, observed, in a far more numerous number than previously estimated, in *Hinode* data (e.g. [42]). Although it is not clear, yet, whether all jets escape the Sun gravitational attraction and feed the wind, it has been estimated that they may provide about 1/10 of the wind mass flux. Hence, they do not seem to contribute appreciably to the wind flux.

We conclude, from the previous two sections, that the latitudinal changes of the solar wind structure, over the solar cycle, are a consequence of the spreading of the activity to higher latitudes, as the solar cycle progresses towards its maximum and different activity phenomena occur at an increasingly higher frequency. In terms of wind speed, this means that a progressively larger part of the heliosphere is filled with slow wind, with respect to what occurred at solar minimum.

Whether this corresponds, in the source region of the wind, to different acceleration profiles or whether the initial acceleration does not change but, for instance, the accelerating mechanism operates over a different altitude interval in different wind types, will be examined in the next section.

Wind speed diagnostics in the lower corona

As mentioned above, SOHO has been crucial in providing the capabilities for a diagnostics of outflows in the lower and intermediate corona. The diagnostics is based on the analysis of the doublet lines of the OVI ion, at 103.2 and 103.7 nm, that form via both collisional and radiative excitation. This latter component originates because of the high exciting chromospheric radiation at those wavelengths and it is subject to Doppler dimming: in other words, the OVI lines radiative component in a stationary plasma is always larger than the radiative component from a moving plasma with the same physical parameters.

It is beyond the aim of this review to give the details of this diagnostics, but the interested reader can refer to Kohl et al. for details [43]. We like to point out that the Doppler dimming analysis of OVI lines is *not* a direct measure of the outflow speed, analogous to Doppler shift measuring, but it is a technique by which, once the radiative component of the OVI lines is identified, a model is built until consistency between the observed and the model predicted component is reached. It follows that quite frequently the model parameters are not unique and a range of possibilities, all equally capable of reproducing the value of the radiative component, is usually obtained.

This technique has been applied to data acquired in a polar coronal hole at the time of minimum solar activity and revealed that OVI ions move faster than protons, by, crudely, $\sim 50\%$, all over the sampled ranges of altitudes, i.e., between 2 and 4 solar radii [44]. The precise values of the outflow speed depend on the assumptions of the model about, for instance, the topology of the CH expansion, and/or about the unknown value of the ratio $T_{\text{par}}/T_{\text{perp}}$ between the temperatures along and across the magnetic fieldlines. The acceleration process keeps accelerating plasma beyond four solar radii, although the difference between the speeds of protons and heavy ions decreases with distance.

These results refer to fast wind at minimum solar activity: we may ask whether we have any evidence about the acceleration process of fast wind from polar holes at maximum activity and/or the acceleration process of slow wind from equatorial holes. The outflow speed of Oxygen ions in equatorial holes, during the rising phase of solar activity, turns out to be lower than in polar holes at minimum, by about a factor 2–3, within the first four solar radii. However, the terminal speed from polar and equatorial holes changes by only about 15%, implying that the acceleration process in equatorial holes operates over a more extended range of altitudes than in polar holes (e.g. [45]). Also, if we compare wind from large polar holes at minimum to wind from small polar holes at maximum, we find clues for a similar behavior, because measurements made at 2.4 solar radii indicate a lower speed in small than in large holes [38]. Although a systematic study of the wind speed profile over the solar cycle at coronal altitudes is still missing, the above results give an indication of its behavior showing that, at a given heliocentric distance, lower densities are related to faster wind acceleration (and higher ion heating).

Conclusion and open questions

This brief review obviously cannot give a thorough account of all the relevant issues within the “solar wind sources along the activity cycle” topic. For instance, the problem of the wind generation deep down below coronal levels has not been discussed: are there changes in these deep levels that affect the wind at interplanetary distances? We mentioned before that abundances in fast and slow wind are different: recalling that with FIP bias we refer to the abundance ratio of low to high FIP elements relative to its photospheric value, we know that slow wind has a higher FIP ratio (2–3) than fast wind (1–2); this suggests that basic differences in the formation of slow and fast wind might originate at levels where the ion-neutral fractionation starts occurring.

Over the solar cycle, with different kinds of solar wind prevailing, the element abundances change from solar maximum to solar minimum: if we focus on the fast wind in the last solar minimum, whose average wind speed – as previously mentioned [13] – was only slightly lower than in previous cycles, we measure a very unusual He abundance, on the order of only 1/3 of what observed at earlier minima. This anomalous behavior, in a two-step scenario where the plasma is first heated to a high enough thermal temperature to overcome gravity and next is accelerated to its terminal speed, hints to a decreased energy input to fast wind at lower levels – and ensuing decreased He particle density – followed by the usual accelerating process (e.g. [46]). Hence, solar wind properties change along the solar cycle as well as from one to another solar cycle: some of these changes may be induced by a decreased energy supply from deep atmospheric layers, which may be revealed, as recently suggested (e.g. [47]), by an analysis of photospheric parameters, like the network length scale, that so far have never been seen as pieces of the same puzzle. The situation is apparently easier for abundances in slow wind that, according to a widely accepted scenario, originate from the release of plasma that has been confined in large, long lived, hot loops, where wave heating leads to an enhancement of elements with a low First Ionization Potential (FIP) (e.g. [48]).

Wind research is a quite lively research area and wind changes over the solar cycle help solving basic problems, like wind sources and wind acceleration, by providing clues about what affects the wind behavior. Quite a few issues are still debated and wait for an unambiguous solution. Among those that emerge from the present review, we may list major issues like the fundamental scale for heating and accelerating wind streams and its variation over the cycle; or the precise identification of slow wind sources and of their contribution to the wind mass flux measured in situ; or the role of small structures in fast wind. Hopefully, the future generation of space missions, like the *Solar Orbiter* and the Solar Probe Plus, will be crucial in providing us with the means to solve what are, as of today, still open problems.

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