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Solar wind and its evolution

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By using our previous results of magnetohydrodynamical simulations for the solar wind from open flux tubes, I discuss how the solar wind in the past is different from the current solar wind. The simulations are performed in fixed one-dimensional super-radially open magnetic flux tubes by inputing various types of fluctuations from the photosphere, which automatically determines solar wind properties in a forward manner. The three important parameters which determine physical properties of the solar wind are surface fluctuation, magnetic field strengths, and the configuration of magnetic flux tubes. Adjusting these parameters to the sun at earlier times in a qualitative sense, I infer that the quasi-steady-state component of the solar wind in the past was denser and slightly slower if the effect of the magneto-centrifugal force is not significant. I also discuss effects of magneto-centrifugal force and roles of coronal mass ejections.

Key words: Atmosphere, MHD, planets, solar corona, solar wind, waves.

1. Introduction

Young solar-type stars are generally very active: X-ray flux is up to $\sim$1000 times larger than the present-day sun (Güdel *et al.*, 1997; Güdel, 2004), and the X-ray temperature is also higher (Ribas *et al.*, 2005; Telleschi *et al.*, 2005). Observations of young main sequence stars show very strong magnetic field strengths with an order of kG or even larger (Donati and Collier Cameron, 1997; Saar and Brandenburg, 1999; Saar, 2001; see also Donati and Landstreet, 2009 for recent review), which are much stronger than the average strength of 1–10 G of the current sun. Young stars are generally fast rotators and strong magnetic fields are generated by strong differential rotation through dynamo activities of magnetoconvection (e.g., Brun *et al.*, 2004). As time goes on, a star loses its angular momentum through magnetic stellar wind (Weber and Davis, 1967) and the magnetic activities become weak (e.g., Ayres, 1997).

Solar wind is hot plasma emanating from the Sun, and the mass loss rate amounts to $\sim 10^{12}$ g s^{-1} ($2 \times 10^{-14} M_\odot$ yr^{-1}) at present. As inferred from high activity of young solar-type stars, I expect that the solar wind was stronger at earlier times. Wood *et al.* (2002, 2005) observed asterospheres of low-mass stars by the Hubble space telescope and determined the mass loss rates. The estimated mass loss rates show a decreasing trend with time, except for very young stars, thought there is still a large scatter in the data, partly because the observed stars range from very low-mass to near solar-mass stars[1]. At the very early epoch, the mass loss rate seems to be saturated at $\sim$100 times of the present solar value, but some very young stars show lower mass loss rates than the present Sun.

The solar wind roughly consists of two components. The first component is called fast solar wind with speed of 700–800 km s^{-1} at the earth orbit. Fast solar wind is more steady and streams out from coronal holes which generally corresponds to open magnetic flux tube regions. The other component is slow solar wind with speed $\lesssim$400 km s^{-1}. Slow wind is more complex and transient, and in most cases comes from lower latitude regions. Recent HINODE observations show that some portions of the slow wind appear to be originating from open flux tubes near active regions (Imada *et al.*, 2007; Sakao *et al.*, 2007; Harra *et al.*, 2008), while there are still debates of other sources for slow wind.

As other types of magnetized plasma from the sun, coronal mass ejections (CMEs) also are supposed to affect atmospheres of planets especially at early times. In this paper, however, I mainly focus on solar wind from open magnetic flux tubes, and briefly mention effects of CMEs afterward. Our group has carried out forward numerical modeling of the solar wind by using direct magnetohydrodynamical (MHD) simulations, in which we can directly test the response of the solar atmosphere to the surface fluctuations and properties of magnetic fields. By using the results of the simulations with parameters suitable for the younger sun, I discuss the solar wind evolution.

2. Simulation Model

In this section, I briefly describe the simulations of the solar wind. For detail, please refer to Suzuki and Inutsuka (2006, SI06, hereafter). In order to cover the region with huge density contrast from $\rho = 10^{-7}$g cm^{-3} at the photo-

[1] Although the observed stars include not only G-type (solar-analogue) stars but also lower mass K- and M-type stars, it is worth discussing trends because the mechanism of mass loss of these stars are supposed to be similar; the stellar wind is accelerated by wave and turbulent motions associated with magnetic field driven by fluctuation in a surface convective zone.

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sphere to $\rho \sim 10^{-21}$g cm^{-3} at the outer simulation boundary located at $\approx$0.1 astronomical unit (AU), simple one dimensional (1-D) open flux tubes are adopted. The effects of super-radial expansion of flux tubes are incorporated by taking into account an expansion factor in the conservation of magnetic flux of radial (r) component, B_r:

$$B_r r^2 f(r) = \text{const.}, \tag{1}$$

where $f(r)$ is a super-radial expansion factor. Most of the solar surface is covered by closed magnetic loop structure. Then, open flux tubes rapidly open above these loops; f is introduced to consider this effect. The same function as in Kopp and Holzer (1976) is adopted for $f(r)$ (see Suzuki and Inutsuka (2006) for detail).

In SI 06 we input the transverse fluctuations of the field line by the granulations at the photosphere. Amplitude, $\langle dv_\perp \rangle$, at the photosphere is chosen to be compatible with the observed photospheric velocity amplitude $\sim$1 km s^{-1} (Holweger *et al.*, 1978). SI06 tested various types of spectra; in this paper I discuss the results of the power spectra in proportion to $1/\nu$, where ν is frequency. The surface fluctuations generate upgoing Alfvén waves which contribute to the acceleration of the solar wind in upper regions. At the outer boundaries, a non-reflecting condition is imposed for all the MHD waves, which enables us to carry out simulations for a long time until quasi-steady state solutions are obtained without unphysical wave reflection.

SI06 dynamically treat the propagation and dissipation of the waves and the heating and acceleration of the plasma by solving ideal MHD equations with the relevant physical processes, including the sun's gravity, radiative cooling, and thermal conduction (Suzuki and Inutsuka, 2005, SI06). I do not take into account stellar rotation, which may be important for very young stars. For the initial condition, we assume a static atmosphere with temperature $T = 10^4$ K in order to see whether the atmosphere is heated up to coronal temperature and accelerated to accomplish the transonic flow. From $t = 0$, the transverse fluctuations are injected from the photosphere and continue the simulations until the quasi-steady states are achieved.

3. Solar Wind Response to Surface Condition

By injecting fluctuations from the photospheric surface, the initially cool and static atmosphere is effectively heated and accelerated by the dissipation of the generated upgoing Alfvén waves. The sharp transition region which divides the cool chromosphere with $T \sim 10^4$ K and the hot corona with $T \sim 10^6$ K is formed owing to a thermally unstable region around $T \sim 10^5$ K in the radiative cooling function (Landini and Monsignori-Fossi, 1990). The hot corona streams out as the transonic solar wind (see Suzuki and Inutsuka, 2005, and SI06 for detail).

The heating and acceleration of the solar wind plasma in inner heliosphere results from the dissipation of Alfvén waves. In the simple 1-D treatment, Alfvén waves mainly dissipate via nonlinear mode conversion; slow MHD waves are nonlinearly generated from outgoing Alfvén waves and the slow MHD waves are damped by shock formation as a result of steepening of wave shape. The shocks also heat up surrounding plasma, which play a central role in the heating of the solar wind plasma. Magnetic pressure associated with the Alfvén waves decreases with height as a result of the successive dissipation process, which directly pushes the plasma outward (momentum input) in addition to gas pressure.

The young sun is more active than the present-day sun, and therefore, I expect that surface fluctuations are stronger. The properties of the magnetic fields are also supposed to be very different. I discuss how properties of the solar wind are affected by fluctuation amplitudes and magnetic fields at the solar surface.

3.1 Dependence on surface fluctuation amplitude

Figure 1 shows the response of the solar wind plasma to the surface fluctuations with different amplitudes, $\langle dv_\perp \rangle =$ 1.4 km s^{-1}, 0.7 km s^{-1} and 0.4 km s^{-1}. The intermediate case ($\langle dv_\perp \rangle = 0.7$ km s^{-1}) is a reference case which explains the present-day solar wind.

The maximum temperature of $\langle dv_\perp \rangle = 0.4$ km s^{-1} case is $\simeq 5\times10^5$ K (Table 1), which is cooler than the usual corona. The density is lower than the fiducial case by 1–2 orders of magnitude because the sufficient mass cannot be supplied to the corona by the chromospheric evaporation owing to the low temperature; the evaporation is drastically suppressed as T decreases, since the conductive flux ($F_c \propto T^{5/2}\frac{dT}{dr}$) sensitively depends on T. As a result, the mass flux (ρv_r) becomes much lower, by a factor of $\sim$50, than that of the present solar wind.

On the other hand, the larger $\langle dv_\perp \rangle = 1.4$ km s^{-1} case gives larger coronal density, although the coronal temperature is only slightly higher than the temperature of the reference case. As a result of the dense corona, the mass flux of the solar wind is $\sim$10 times larger (Table 1). This case shows complicated structure of temperature and density near the solar surface. The temperature starts to increase from a deeper location around $r \simeq 0.005R_\odot$ than the other cases. Thanks to this, the decrease of the density is slower (larger pressure scale height) so that the density around $r = 1.01R_\odot$ is two orders of magnitude larger than that of the reference case with $\langle dv_\perp \rangle = 0.7$ km s^{-1}. However, the temperature decreases slightly instead of showing a monotonical increase; it cannot go over the peak of the radiative cooling function at $T \simeq 10^5$ K (Landini and Monsignori-Fossi, 1990) because the radiative loss is efficient, owing to the large density. The temperature again increases from $r \simeq 1.03R_\odot$ and above there the corona forms. The coronal density is larger than the that of the reference case as explained above.

A striking feature is that the mass flux of solar winds sensitively depends on the input wave amplitude at the solar photosphere. Since the injected energy is proportional to the square of $dv_\perp$, the difference of the input energy between the small amplitude case ($\langle dv_\perp \rangle = 0.4$ km s^{-1}) and the large amplitude case ($\langle dv_\perp \rangle = 1.4$ km s^{-1}) is $\simeq$12. However, the output mass flux of the large amplitude case is $\sim$400 times larger than the mass flux of the small amplitude case.

The sensitive behavior on the surface amplitude can be understood by reflection and nonlinear dissipation of Alfvén waves (SI06). Because the heating is smaller, the temperature is lower in the smaller $\langle dv_\perp \rangle$ cases. Then,

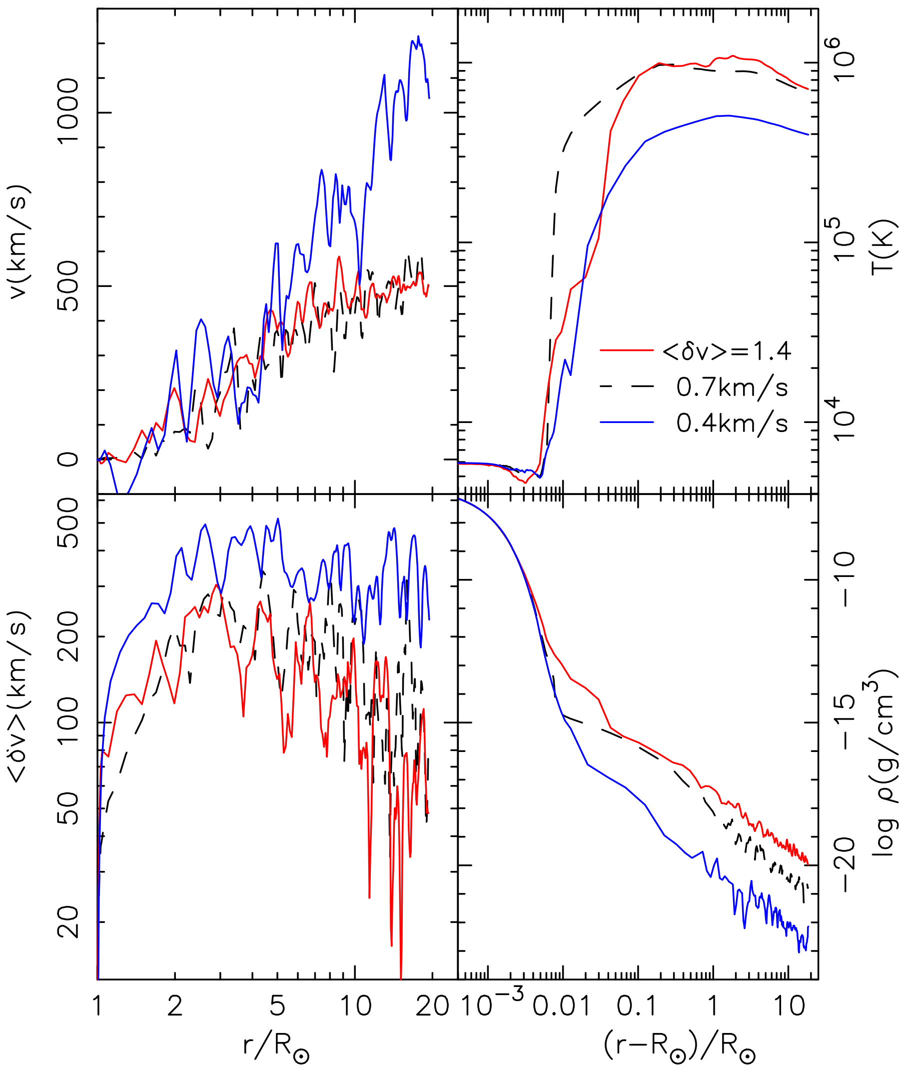

Fig. 1. Structures of corona and solar wind for different $\langle dv_\perp \rangle = 0.4$ (blue), 0.7 (black dashed), and 1.4 km s^{-1} (red). I plot solar wind speed, v_r (km s^{-1}) (top left), temperature, T (K) (top right), density in logarithmic scale, $\log(\rho(\mathrm{g\ cm^{-3}}))$ (bottom right), and rms transverse velocity, $\langle dv_\perp \rangle$ (km s^{-1}) (bottom left). Each variable is averaged with respect to time during 28 min (the longest wave period considered).

Table 1. Summary of model parameters and results. The first column shows the input amplitudes of the surface fluctuation. The second column presents the maximum temperatures in the simulation regions. The third column shows proton number density at 1 AU, which is calculated from n_p at the outer boundary of the simulation by assuming the conservation of the mass flux ($n_\mathrm{p} v r^2 f =$ const.) with constant speed from 0.1 AU to 1 AU. The fourth column shows the solar wind speeds at 0.1 AU ($\simeq$the outer boundary of the simulation region). The fifth column shows mass flux of the solar wind at 1 AU, which is the product of the third and fourth columns.

$\langle dv_\perp \rangle$	T_max	$n_{\mathrm{p,1\,AU}}$	$v_{0.1\,\mathrm{AU}}$	$(n_\mathrm{p} v)_{1\,\mathrm{AU}}$
1.4 (km/s)	1.2×10^6 (K)	50 (cm^{-3})	500 (km/s)	2.5×10^9 (cm^{-2} s^{-1})
0.7 (km/s)	1.0×10^6 (K)	5 (cm^{-3})	550 (km/s)	2.8×10^8 (cm^{-2} s^{-1})
0.4 (km/s)	0.5×10^6 (K)	0.05 (cm^{-3})	1200 (km/s)	6×10^6 (cm^{-2} s^{-1})

the scale height becomes smaller and the density decreases rapidly. The Alfvén speed, $v_\mathrm{A}(= B_r/\sqrt{4\pi\rho})$, changes more rapidly due to the rapid decrease of density and the wave shape is largely deformed, which enhances the reflection. When the input wave energy decreases, a positive feedback operates; a smaller fraction of the energy can reach the coronal region. As a result, the density and mass flux of the solar wind becomes much smaller than the decreasing factor of the input energy.

In addition to the effect of the wave reflection, the nonlinear dissipation of the Alfvén waves also plays a role in the sensitive dependence on the input wave energy (SI06). When the input wave energy becomes smaller, the density becomes smaller as explained above. Then, the nonlinearity of Alfvén wave, $dv_\perp/v_\mathrm{A}$, decreases, not only because the amplitude, $dv_\perp$, is smaller but also because the Alfvén speed, $v_\mathrm{A}(\propto 1/\sqrt{\rho})$, is larger. Therefore, the Alfvén waves do not dissipate and the heating is reduced, which further decreases the density; this is another type of positive feedback, which also results in the sensitive dependence of the density on the input wave energy.

3.2 Magnetic fields

At earlier epochs the sun is expected to have possessed stronger magnetic field than today, as inferred from observations of young stars (Donati and Collier Cameron, 1997; Saar and Brandenburg, 1999). The configuration of magnetic fields as well as field strength plays an essential role in determining the physical solar wind conditions. In the 1-D treatment as adopted in this paper, a super-radial expansion factor, f, determines the geometry of flux tubes. Wang and Sheeley (1990, 1991) showed that the solar wind speed at $\sim$1 AU is anti-correlated with f from their long-term observations. This can be naively understood by energetics consideration; since f directly determines an adiabatic loss of plasma in flux tubes, solar wind plasma in largely expanding (larger f) flux tubes undergoes larger energy loss.

By the comparison of the outflow speed obtained by interplanetary scintillation measurements with observed photospheric field strength Kojima *et al.* (2005) have found that the solar wind velocity is better correlated with surface magnetic field strength, divided by the expansion factor, $B_{r,0}/f$: They claim that $B_{r,0}/f$ is a better index for the speed of solar wind than individual $1/f$ or $B_{r,0}$. The correlation between $B_{r,0}/f$ and solar wind speed is well explained by Alfvén waves in expanding flux tubes (Suzuki, 2006). Because the energy flux of input Alfvén waves is proportional to $B_{r,0}$, the positive correlation of solar wind speed with $B_{r,0}$ is quite natural. The negative correlation with f reflects the adiabatic loss of Alfvén waves in expanding tubes as explained above.

One can understood the correlation more specifically from nonlinear dissipation of Alfvén waves as well. The nonlinearity of the Alfvén waves, $\langle dv_\perp\rangle/v_A$ is controlled by $v_A \propto B_r \propto B_{r,0}/f$ in the outer region where the flux tube is already super-radially open. Wave energy does not effectively dissipate in the larger $B_{r,0}/f$ case in the subsonic region because of relatively small nonlinearity, and more energy remains in the supersonic region. In general, energy and momentum inputs in the supersonic region result in higher wind speed, while those in the subsonic region raise the mass flux (ρv_r) of the wind by increasing density (Lamers and Cassinelli, 1999). This indicates that the solar wind speed is positively correlated with $B_{r,0}/f$.

4. Evolution of Solar Wind

I have described based on our numerical simulations that the solar wind from open magnetic flux tubes is mainly controlled by the three parameters: surface fluctuation amplitude, $\langle dv_\perp\rangle$, radial magnetic field strength at the photosphere, $B_{r,0}$, and super-radial expansion factor, f, of flux tubes. Thus, if I can determine these parameters for the young sun, I can estimate the properties of solar wind at that time.

4.1 Surface fluctuation amplitude

I can speculate that $\langle dv_\perp\rangle$ was larger at earlier times from circumstantial evidences. First, the rotation of the sun should be faster at earlier times because of loss of angular momentum with time. Hence, in addition to surface convection, interior differential rotation will lead to stronger surface fluctuations. From observational facts, younger stars show higher X-ray activities as discussed in the introduction section, which also anticipates larger $\langle dv_\perp\rangle$. An important issue is that a small increase of $\langle dv_\perp\rangle$ leads to a large increase of mass flux of solar wind.

4.2 Magnetic field—$B_{r,0}$ & f—

$B_{r,0}$ is also supposed to be larger than today as implied from observations of young stars (Donati and Collier Cameron, 1997; Saar and Brandenburg, 1999). Rossby number, R_0, which is defined as the ratio of stellar rotation period to convective turn-over time, is an important index which describes stellar magnetic activities (Noyes *et al.*, 1984). Surface magnetic field strength, $B_{\rm ph}$, multiplied by a magnetic areal filling factor, $\mathcal{F}$, is well-correlated with R_0^{-1}. Stars with small $R_0 < 0.1$, which correspond to fast rotating young stars, have $B_{\rm ph}\mathcal{F} = 1$–$10$ kG (Saar, 2001). In some stars $\mathcal{F}$'s are obtained and the values are 50–70%, which shows that $B_{\rm ph}$ is an order of 10 kG in these stars.

If all the magnetic flux is open to the interplanetary space, I can set $f = 1/\mathcal{F}$; in reality, however, closed loop structure is more dominant, and then, it is expected that $f \gg 1/\mathcal{F}$. I speculate that super-radial expansion, f, of the young sun was larger as discussed from now, although it is not simple to pin down the specific value. Recently, the configuration of magnetic field has been observed in a number of low-mass stars (e.g. Donati *et al.*, 2008). Fast rotating solar mass stars possess non-axisymmetric poloidal components with substantial toroidal fields (see figure 3 of Donati and Landstreet (2009)). This implies that the field configuration is quite complicated, and is very different from ordered dipole structure. In comparison with 11-year periodicities of present-day solar activity[2], the properties of magnetic field of the earlier sun resemble the condition of the present-day solar maximum rather than the solar minimum.

During the solar minimum periods, the solar wind consists of fast wind which is from mid- to high-latitude regions, and slow wind from lower-latitude regions. On the other hand, during the solar maximum periods, most of the regions are occupied by transient slow wind (McComas *et al.*, 2008). At the solar maximum magnetic fields are dominated by a dipole component, while at the solar minimum higher multi-pole moments become more important showing more complex field configuration (Hakamada *et al.*, 2005). Because the surface is mostly covered with closed magnetic fields during the solar maximum, the field strength in the outer regions is not as strong as that at the solar minimum although the field strength at the photosphere is stronger. This fact shows that f is larger during the solar maximum. The speed of the solar wind during the solar maximum is slower, which is consistent with the observational trend (Kojima *et al.*, 2005), because of larger adiabatic loss in open magnetic flux tubes.

Based on these considerations, namely (i) the magnetic field structure of the young sun more resembles the current solar maximum than the solar minimum, and (ii) open flux tubes show larger expansion during the solar maximum because larger surface area is occupied by closed structure, I infer that open magnetic flux tubes of the young sun have

[2] I would like to note that the 11-year duration is modulated with time depending activity even in last several hundred years (Miyahara *et al.*, 2008).

much larger f. I speculate that, even though the magnetic field strength at the footpoints is stronger, $B_{r,0}/f$, is smaller at earlier time.

4.3 Solar wind in the past

I would like to discuss how the properties of solar wind change in the past based on the simulation results. I have stated that $\langle dv_\perp \rangle$ was larger and $B_{r,0}/f$ was smaller at earlier times. These conditions imply considerably denser but slightly slower solar wind in the past, although it is quite difficult to quantitatively determine the physical condition.

4.4 Limitations

In this paper I neglect the effect of magneto-centrifugal force in driving winds (Weber and Davis, 1967; Mestel, 1968). Under the typical solar condition, if the rotation period is 4 days (6–7 times faster than the present sun) or less, magneto-centrifugal force plays an important role and the wind speed becomes significantly higher (Newkirk, 1980).

Recently, Holzwarth and Jardine (2007) calculated the evolution of solar wind by considering megneto-centrifugal force. They concluded that the solar wind in the past was faster but not so much denser than today, which are different from my conclusion. Holzwarth and Jardine (2007) assumed a constant density at a 'reference point', 1.1 times of the stellar radius, which strongly constrains the mass loss rate (see, e.g. section 3 of Lamers and Cassinelli, 1999). In realistic situations, the density at the coronal base, accordingly the density at the reference level, is determined by the energy balance among heating, thermal conduction, and radiative cooling (SI06; see also Suzuki 2007 for different types of stars). The base densities of young active stars are larger than those of quiescent stars, and the mass loss rates are supposed to be significantly larger. In this case the wind speed becomes slower because more mass needs to be pushed away. The same tendency on the coronal base density is also reported by Stereborg *et al.* (2011) who performed 3D MHD simulations for a young sun.

It is not still possible to discuss the wind speed in a quantitative sense at the moment. My conclusion of the slightly slower wind in the past might be corrected because magneto-centrifugal force could be significant. On the other hand, I suppose that the wind speed is not so high as estimated by Holzwarth and Jardine (2007) bacause the coronal base density should larger at that time than their assumption. Accordingly, the density of the solar wind could be larger than those calculated in Holzwarth and Jardine (2007).

In this paper I focus on quasi-steady-state solar wind from open magnetic flux regions, and do not consider CMEs. While the quasi-steady-state component dominantly contributes to the total mass loss from the present-day sun than CMEs, at early times CMEs might play a more important role because of stronger magnetic activities. From the fossil record on the lunar surface, it is inferred that the speed of solar wind was faster in the past (Newkirk, 1980; Ray and Heymann, 1980). I infer that the fossil record comprises effects of both quasi-steady state component and CMEs. If strong CMEs dominantly contribute to the mass loss, the bulk speed of plasma flow from the sun would be recognized as higher. I speculate that the fossil inprint on the moon is connected with high CME activities at early epochs.

5. Summary

Based on our previous results of MHD simulations, I discuss the evolution of the quasi-steady-state component of solar wind from open flux tubes. The properties of the solar wind are determined by the three parameters, surface fluctuation amplitude, magnetic field strength, and expansion of open flux tube. Referring to observational data of young low-mass stars, I suppose that the surface amplitude was larger and the ratio of field strength to flux tube expansion was smaller. Following this speculation, the solar wind in the past was dense and slightly slower than today, while if the effect of magneto-centrifugal force is taken into accout, the speed of the solar wind might be higher at very early epoch than my conclusion. CMEs are also supposed play a more important role in the past than today because of higher magnetic activities. In order to understand the effects of solar magnetized plasma on the atmospheres of planets, we need to understand the evolution of CMEs as well as the evoltuion of quasi-steady-state solar wind.

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