Response of Solar Wind on Extreme Solar Activity

Takeru K. Suzuki
Department of Physics, Nagoya University, Furo-cho, Chikusa-ku, Nagoya, Aichi 464-8602, Japan
E-mail: stakeru@nagoya-u.jp

Abstract. We investigate how the mass loss by the solar wind depends on the solar activity levels, particularly focusing on the solar wind during extremely high activity. We perform forward-type magnetohydrodynamical (MHD) numerical experiments for Alfvén wave-driven solar winds with a wide range of the input Poynting flux from the photosphere. Increasing the magnetic field strength and the turbulent velocity at the solar photosphere from the current solar level, the mass loss rate rapidly increases at first owing to the suppression of the reflection of the Alfvén waves. The surface materials are lifted up by the magnetic pressure associated with the Alfvén waves, and the cool dense chromosphere is extended to 10% of the stellar radius. The dense atmospheres enhance the radiative losses and eventually most of the input Poynting energy from the surface escapes by the radiation. As a result, there is no more sufficient energy remained for the kinetic energy of the wind; the solar wind saturates for the extreme activity level, as observed in Wood et al. The saturation level is positively correlated with the average magnetic field strength contributed from open flux tubes. If the field strength is a few times larger than the present level, the mass loss rate could be as high as 1000 times.

1. Introduction
Young solar-type stars are generally very active in X-ray and UV radiation (1), which is probably related to the strong magnetic field with an order of kilo-Gauss (2). The mass loss rate of stars with surface convection is also larger for larger X-ray luminosity, up to ≈ 100 times of the mass loss rate of the Sun, but it saturates for very active ones, which is discussed from the change of magnetic topology (3; 4; 5). The relation between the stellar magnetic field and the wind has lately attracted considerable attention and has been extensively studied these days (6; 7). In this article, we briefly review our recent results on stellar winds from young active solar-type stars.

2. Simulation or the Present Solar Wind
We briefly explain our MHD simulations for the solar and stellar wind (8; 9; 10). We follow the time evolution of velocity, \( v \), density, \( \rho \), temperature, \( T \), and magnetic fields, \( B \), in a single open flux tube by solving MHD equations with radiation cooling (11; 12; 13) and thermal conduction by Coulomb collisions (Spitzer conductivity). The simulation region covers from the photosphere to the interplanetary space (0.3 AU), which is the biggest advantage of our setup because we can determined the mass loss rate directly from the physical properties at the photosphere where various detailed observational data are available.

We show the result for the typical high-speed solar wind introduced in (8) in Figure 1. We set up an initially static \( v = 0 \) and cool \( (T = 10^4 \text{ K}) \) atmosphere and begin the simulation with...
injecting transverse fluctuations with 0.7 km s$^{-1}$ of the surface convection from the photosphere. The figure clearly exhibits that the atmosphere is heated up to the coronal temperature with $T \approx 10^6$ K and accelerated to 700-800 km s$^{-1}$ when the quasi-steady-state condition is obtained.\footnote{Movie is available at www.ta.phys.nagoya-u.ac.jp/stakeru/research/swhr560_2.mpg} The transverse fluctuations drive Alfvénic waves that propagate upwardly. While a large fraction ($\sim 90\%$) of the input Poynting flux by the Alfvénic waves is reflected back downward, a sufficient energy is transmitted to the coronal region. The main dissipation channel is the nonlinear mode conversion to compressive waves; the fluctuation of the magnetic pressure of the Alfvénic waves excites longitudinal perturbation, most of which is slow MHD waves in the low-\(\beta\) (magnetically dominated) condition\footnote{14th AIAC IOP Publishing Journal of Physics: Conference Series 642 (2015) 012027 doi:10.1088/1742-6596/642/1/012027} (14). These slow MHD waves eventually steepen to form shocklets and dissipate to heat up the surrounding plasma.

A characteristic feature of the excitation of compressive waves is that density perturbation could be observed. Recently, AKATSUKI, Japanese satellite originally planned as a Venus climate orbiter, observed the regions in $1.5 - 20 R_\odot$ ($R_\odot$ is the solar radius) where the solar wind is accelerated\footnote{2}, and detected density fluctuations there\footnote{3}, whereas the simulated density amplitude exceeds the observed value (Fig. 8 of (16)) probably because of the limitation of our treatment (see below) and/or the effect of the line-of-sight integration in the observation. Because it is difficult for compressive waves to propagate from the photosphere to the coronal region owing to the dissipative character\footnote{4}, these density fluctuations are supposed to be excited in situ; the nonlinear mode conversion from Alfvénic waves is one of the possible mechanisms.

Since in our simulation we consider the energy transfer in the one-dimensional flux tube (“1.5D” approximation with solving the three components of $\mathbf{v}$ and $B$), we cannot treat cascading Alfvénic turbulence, which is supposed to play a role in the heating and driving the solar wind\footnote{5; 6; 7}. In realistic situations, the incompressive turbulent cascade and the above mentioned generation of compressive waves both contribute to the coronal heating and solar wind acceleration in a cooperating manner. In fact, our simulation is extended to two dimensional (“2.5D”) flux tubes recently\footnote{8; 9} to study both turbulent cascade and nonlinear generation compressive waves.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig1}
\caption{Time evolution of the MHD simulation for the solar wind (8). The left panel presents the initial condition and the right panel presents the snapshot at $t = 2573$ min. after the quasi-steady state condition is achieved. The four small panels in each panel shows radial velocity ($v$ km s$^{-1}$; upper left), temperature ($T$ K; upper right), root-mean-squared velocity amplitude of Alfvénic waves ($\sqrt{\langle dv^2 \rangle}$ km s$^{-1}$; lower left), and density ($\rho$ g cm$^{-3}$; lower right).}
\end{figure}
3. Wind from Active Stars

3.1. Rapid Increase and Saturation

![Graph showing the relation between input energy and wind kinetic energy](image)

**Figure 2.** Final kinetic energy of the stellar wind for the input Poynting flux injected by Alfvénic waves from the photosphere. Colors indicate the average magnetic field strength contributed from open magnetic field regions, $B_{r,0}f_0$. The solid lines indicate the conversion factor, $c_E = 0.001, 0.01, 0.1$.

Our forward-type simulation can determine the mass loss rate of the wind by the properties at the photosphere. By utilizing this advantage, we investigate the response of the atmosphere on a change of the velocity fluctuation, $\delta v$, and the strength and configuration of the magnetic field. Although we have three parameters on the magnetic field, we here focus on $B_{r,0}f_0$, where $B_{r,0}$ is the radial magnetic field strength and $f_0$ is the areal filling factor of open magnetic field regions measured at the photosphere; $B_{r,0}f_0$ denotes the average magnetic field strength contributed from open flux regions. We performed 163 simulation runs for stellar winds from a star with the solar mass and radius by changing these parameters (see (23) for detail).

Figure 2 shows the relation between the input energy by the Alfvén wave in units of luminosity, erg s$^{-1}$, from the photosphere (horizontal axis) and the kinetic energy luminosity of the stellar wind (vertical axis). Conversion factor, $c_E$, from the input wave energy to the output kinetic energy is also shown by solid lines. As easily expected, one can see a positive correlation between the input energy and the wind kinetic energy within a range of $c_E = 0.001 - 0.1$. However, if we focus on the data with a single $B_{r,0}f_0$, the trend is not monotonic; the trend for the data with pink ($B_{r,0}f_0 = 2.5$ G) is shown by arrows, for example; the kinetic energy rapidly increases initially with an increasing input energy but eventually saturates or even decreases.

The rapid increase of the kinetic energy in the regime of small input energy can be explained by the suppression of the reflection of Alfvénic waves. The left panel of Figure 3 compares the time-averaged density structures of a present sun case (blue) and an active young sun case with larger $\delta v$ and $B_{r,0}f_0$ (red). In the active case, the decrease of the density is much slower, which indicates that the atmospheric gas is lifted up to the upper region. This is mainly because the magnetic pressure of the Alfvénic waves contributes to the hydrostatic equilibrium against the gravity in addition to the usual gas pressure gradient force. As a result, the change of the Alfvén speed (right panel) is more gradual in this case. This is in contrast to the current sun case, in which the Alfvén speed $= B_r/\sqrt{4\pi \rho}$ increases drastically from the chromosphere to the
Figure 3. Comparison of the time-averaged profiles of density (left) and Alfvén speed (right) for a present sun case (blue) and an active young sun case (red).

coronal region because of the rapid decrease of the density. The profile of the Alfvén speed controls the reflection of Alfvénic waves; a rapid change of Alfvén speed generally enhances the reflection because of the deformation of the shape of propagating waves. Therefore, in the active case a larger fraction of the input energy penetrates to the corona. This argument indicates that the transmitted energy of the Alfvénic waves depends sensitively on the input energy; a small change of the injected energy leads to a large difference of the transmitted wave energy to the corona, and accordingly the final kinetic energy of the wind.

Figure 4. Comparison of the mass loss rate and the radiation flux. The color symbols are from our simulation, and the black symbols are observational data from (4).

The saturation or decrease of the kinetic energy on an increasing input energy is because of the rapid enhancement of the radiation loss. As the input energy increases, the density in the atmosphere also increases, which gives larger mass loss rate. The radiative cooling in the optically thin coronal region is proportional to the density squared. Therefore, the radiation loss rapidly increases for an increasing input energy, and eventually the sufficient energy is not remained for the kinetic energy of the wind.
In order to compare our simulation results to the observation of solar-type stars (3; 4; 5), we show the wind kinetic energy on the radiative flux in Figure 4 (see (23) for detail). The observed maximum mass loss is $\approx 100$ times of the current mass loss rate from the Sun, our result shows that some cases give even larger mass losses up to $\approx 1000$ times of the present solar mass loss for strong magnetic field, $B_{r,0} f_0 = 10$ G.

3.2. Extended Chromosphere

![Figure 5. Comparison of the temperature structures of the current sun case (blue) and the active sun case (red).](image)

Most of the simulation runs with a large energy input by the Alfvénic waves from the photosphere show an extended chromosphere because of the support from the magnetic pressure of the Alfvénic waves (Figure 3). Figure 5 compares the snapshot temperature structures of the current sun case and the active young sun case. In the active sun case, the chromosphere extends to $\approx 10\%$ of the stellar radius, which is in contrast to the very thin ($< 1\%$) chromosphere of the current sun. Interestingly, Czesla et al (24) reported that a young Sun-like star has a very extended chromosphere up to $\approx 15\%$ of the stellar photosphere based on their observation of the exoplanet system with the Rossiter-McLaughlin effect of chromospheric lines.

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