SOLAR X-RAY JETS, TYPE-II SPICULES, GRANULE-SIZE EMERGING BIPOLES, AND THE GENESIS OF THE HELIOSPHERE

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ABSTRACT

From *Hinode* observations of solar X-ray jets, Type-II spicules, and granule-size emerging bipolar magnetic fields in quiet regions and coronal holes, we advocate a scenario for powering coronal heating and the solar wind. In this scenario, Type-II spicules and Alfven waves are generated by the granule-size emerging bipoles in the manner of the generation of X-ray jets by larger magnetic bipoles. From observations and this scenario, we estimate that Type-II spicules and their co-generated Alfven waves carry into the corona an area-average flux of mechanical energy of ~ 7 x 10^5 erg cm^{-2} s^{-1}. This is enough to power the corona and solar wind in quiet regions and coronal holes, and therefore indicates that the granule-size emerging bipoles are the main engines that generate and sustain the entire heliosphere.

Key words: Sun: heliosphere – Sun: corona – Sun: chromosphere – Sun: surface magnetism – Sun: magnetic topology – Sun: activity

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1. INTRODUCTION

The heliosphere, the bubble that the solar wind blows in the interstellar wind, is ~ 10^4 times bigger in diameter than the Sun. It is the largest material entity produced by the Sun's magnetism. The ~ 10^6 K temperature of the Sun's outer atmosphere, the corona, and the corona's out-flowing extension, the solar wind, are somehow produced by the Sun's magnetic activity (e.g., Goldstein 1998). Determination of the dominant mechanisms by which the magnetic field permeating the solar atmosphere powers coronal heating and the solar wind is an enduring primary quest of solar research.

Nearly all of the quasi-steady solar wind escapes along the coronal magnetic field that is pulled open and held open by the solar wind itself, and most of this field stems from quiet regions and coronal holes, not from active regions (e.g., Zirker et al 1977; Holtzer 1992). A basic concept for the genesis of the heliosphere, one long advocated by many researchers, is that in quiet regions and coronal holes coronal heating and the solar wind are powered by fine-scale explosive magnetic activity involving reconnection low in the magnetic network (e.g., Rabin & Moore 1980; Porter & Moore 1988; Parker 1991; Moore et al 1991, 1999, 2004; Axford & McKenzie 1992; Schrijver et al 1998; Falconer et al 1998, 2003; Fisk et al 1999; McIntosh et al 2007; De Pontieu et al 2009; Heggland et al 2009; Rouppe van der Voort et al 2009; Roberts 2010). In this paper, we point out new morphological evidence and new quantitative evidence for a specific version of this basic idea, the picture envisioned in Porter & Moore (1988) and Moore et al (1991, 1999) and refined in Falconer et al (2003) and Moore et al (2004). From a synthesis of recent observations from the *Hinode* solar space mission of coronal X-ray jets, chromospheric Type-II spicules, and photospheric granule-size emerging bipolar magnetic fields (hereafter referred to as EBs), we estimate the flux of mechanical energy put into the corona in quiet regions and coronal holes by Type-II spicules and co-produced Alfven waves.

To power coronal heating and the solar wind in either coronal holes or quiet regions the required flux of non-thermal energy entering the base of the corona is ~ 5×10^5 erg cm^{-2} s^{-1} (Withbroe & Noyes 1977; Withbroe 1988). From the *Hinode* observations, we propose that Type-II spicules are produced in the same manner as X-ray jets by explosive reconnection of a magnetic bipole with impacted feet of coronal fields, that EBs are the bipoles that produce Type-II spicules, and that the production of a Type-II spicule also produces a burst of Alfven waves. From observed quantities, we estimate that the mechanical energy flux carried into the corona in coronal holes and quiet regions by Type-II spicules and Alfven waves produced by EBs is ~ 7×10^5 erg cm^{-2} s^{-1}. Thus, it appears that the entire heliosphere is fueled as depicted in Figure 1, by explosive activity of EBs, each of which is ~ 10^3 times smaller in diameter than the Sun and ~ 10^7 times smaller than the heliosphere.

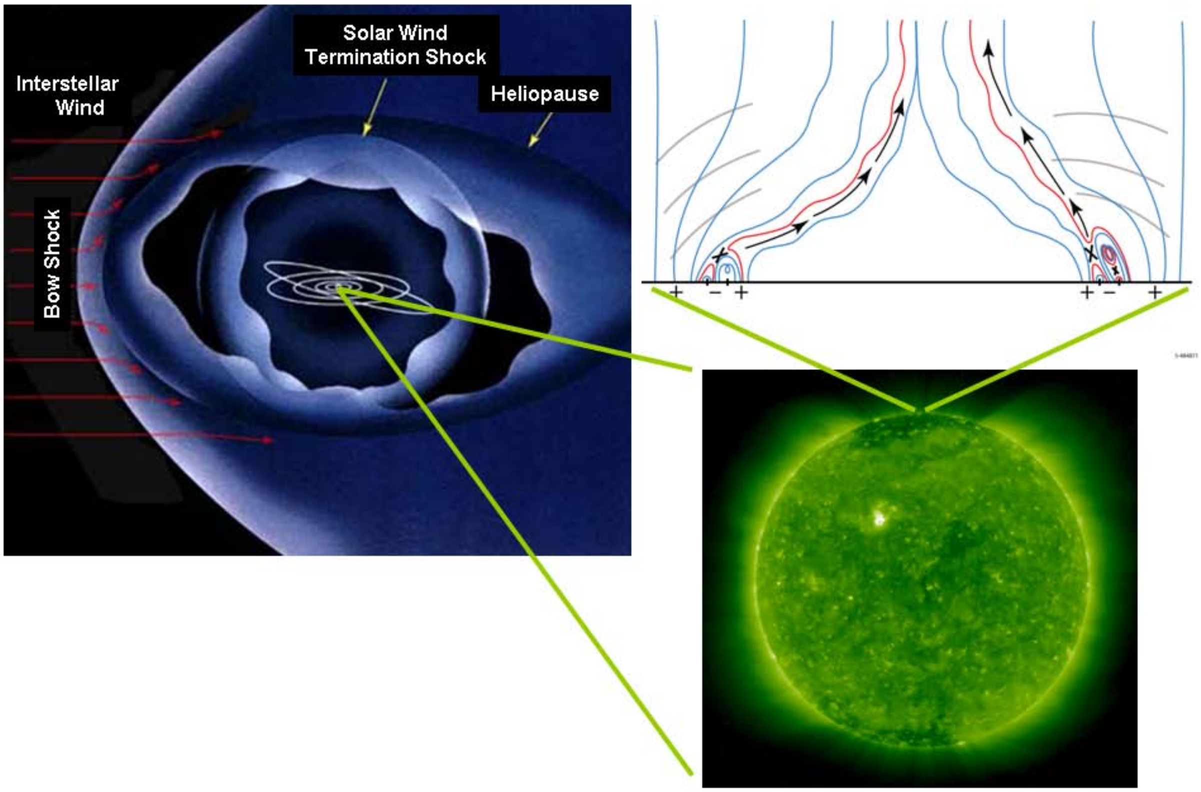

Figure 1. Schematic depiction of the heliosphere and its genesis in the Sun's fine-scale magnetic activity in quiet regions and coronal holes. Left: diagram of the heliosphere. Lower right: STEREO A EUVI 195 Å image of the ~ 1.5 x 10^6 K corona. Upper right: Cartoon of the production of MHD waves and Type-II spicules by EBs.

2. OBSERVATIONS

2.1. X-ray Jets

Solar X-ray jets were discovered and extensively observed with the Soft X-ray Telescope on *Yohkoh* (Shibata et al 1992; Shimojo et al 1996), and their structure and dynamics have been better resolved by the X-Ray Telescope (XRT) on *Hinode*, in movies having 1 arcsec pixels and ~ 1-minute cadence (e.g., Cirtain et al 2007; Savcheva et al 2007, 2009).

Any X-ray jet is rooted in and around a bipolar magnetic field that has emerged into ambient high-reaching unipolar field (Shibata 2001; Shimizu 2002). This basic arrangement of magnetic field is observed to produce a dichotomy of X-ray jets, namely standard jets and blowout jets (Moore et al 2010). In either case, the emerging bipole evidently drives a burst of external reconnection at the interface between the ambient field and the impacted opposite-polarity leg of the bipole. A standard jet is produced by this reconnection if the interior of the bipole remains quasi-static, as in the standard model for X-ray jets (Shibata et al 1992; Shibata 2001). A blowout jet is produced if the interior of the bipole does not remain inert but erupts open in the manner of the magnetic-arcade ejective eruptions that produce coronal mass ejections. The resulting blowout jet is a combination of (1) plasma ejected up along the ambient field by the external reconnection driven by the erupting bipole, and (2) plasma and magnetic field that have erupted from the interior of the bipole and are guided along nearly the same path by the ambient field.

In X-ray jets, the base bipole typically spans ~ 20,000 km or more (Shimojo et al 1996), large enough that most of the bipole's field arches into the low corona, allowing the site of the external reconnection in the production of a standard jet to be in the low corona. This is consistent with the reconnection outflow and hence the jet being enough hotter than the ~ 10^6 K ambient corona to be bright in soft X-ray emission. Also consistent with the external reconnection being in the low corona, the speed of X-ray jets measured in coronal holes from *Hinode*/XRT movies is usually in the range between the sound speed (~ 10^7 cm s^{-1}) and the Alfven speed (~ 10^8 cm s^{-1}) in the ambient low corona (Savcheva et al 2007; Cirtain et al 2007).

In the *Hinode*/XRT movies, standard jets in coronal holes are also often seen to be embedded in upward-propagating Alfven waves of period ~ 200 s and transverse oscillation velocity amplitude ~ 4 x 10^6 cm s^{-1} (Cirtain et al 2007). These waves are plausibly generated in the ambient field in and around the jet by the whipping motion produced low in the ambient field that is released by reconnection to drive the jet (Yokohama & Shibata 1996). Alfven-wave-like whipping and twisting motions of amplitude at least as large as in standard jets have been observed in blowout jets (e.g., Patsourakos et al 2008), and are plausibly produced by a combination of the blowout eruption of the base bipole and its reconnection with the ambient field (Pariat et al 2009).

2.2. Type-II Spicules

Spicules are jets of chromospheric plasma that are rooted in the magnetic network in quiet regions and coronal holes and in the magnetic flux in and around active-region plage. They are like X-ray jets in that they shoot up along magnetic field that reaches high into the corona, but are much smaller and far more numerous. Spicules have widths ranging below ~ 10^8 cm, extend to heights of 5-10 x 10^8 cm above the photosphere, and make up most of the T ~ 10^4 K chromosphere at heights above 2-3 x 10^8 cm (Beckers 1968, 1972; Sterling 2000). The Solar Optical Telescope (SOT) on *Hinode* has taken Ca II H movies of the spicule forest at the limb with unprecedented continous 0.2 arcsec resolution and ~ 10 s cadence. These movies show that much of the spicule forest is made of what are called Type-II spicules, which are narrower, briefer, and three to four times faster than classical spicules, the spicules seen in previous less well resolved chromospheric movies taken from ground-based observatories (e.g., De Pontieu et al 2007a). From comparison of Hα images of ~ 1 arcsec resolution in Lynch et al (1973) of the forest of classical spicules on the limb in quiet quiet regions with the SOT Ca II images in Sterling et al (2010) of the forest of Type-II spicules on the limb in a polar coronal hole, it appears that Type-II spicules are more numerous than classical spicules, but less than twice as numerous. From this and the count of classical spicules in Lynch et al (1973), we surmise that at any time there are ~ 50 Type-II spicules present per supergranule, or ~ 1 Type-II spicule per 2 x 10^{17} cm^2 of surface area in quiet regions and coronal holes.

Because the speed of Type-II spicules is ~ 10^7 cm s^{-1}, an order of magnitude faster than the sound speed in the chromosphere, Type-II spicules are thought to be produced by fine-scale bursts of reconnection low in the magnetic network (De Pontieu et al 2007a). In a SOT Ca II movie of the limb in a coronal hole, Sterling et al (2010) have pointed out that many Type-II spicules expand laterally as they erupt through the high chromosphere, in a manner reminiscent of filament eruptions. From these observed properties, we think that Type-II spicules are plausibly the large class of spicules inferred in Moore et al (2010) to exist, to be miniature counterparts of X-ray jets, and to have a similar standard-jet/blowout-jet dichotomy. This would require each Type-II spicule to have at its base a tiny emerging bipole that produces the spicule by explosive reconnection with the ambient unipolar network field in the low chromosphere. This possibility for the production of Type-II spicules is compatible with the ~ 10^7 cm s^{-1} speed of these spicules in that, as for X-ray jets (Cirtain et al 2007), the speed of the jet roughly equals the Alfven speed in and around the reconnection interface between the emerging bipole and the ambient field: at a height of ~ 1.5 x 10^8 cm in the low chromosphere, the mass density is ~ 10^{-12} gm cm^{-3} (Allen 1973) and the strength of the network field is ~ 30 G (e.g., Moore et al 1991), which values give ~ 10^7 cm s^{-1} for the Alfven speed.

De Pontieu et al (2007b) have shown from SOT Ca II H movies of the chromospheric limb that Type-II spicules are embedded in upward-propagating Alfven waves of period ~ 250 s and transverse velocity amplitude ~ 2 x 10^6 cm s^{-1}. These Alfven waves are similar in period to those in X-ray jets and somewhat smaller in transverse velocity amplitude. If, as we think is plausible, Type-II spicules are small analogues of X-ray jets, then the Alfven waves in and around a Type-II spicule are plausibly generated together with the spicule in the same way as in X-ray jets, by the base bipole's burst of reconnection with the ambient field.

2.3. Granule-Size Emerging Bipoles (EBs)

In quiet regions and coronal holes, photospheric vector magnetograms from the Solar Optical Telescope/Spectropolarimeter on *Hinode* show EBs, randomly scattered emerging bipolar magnetic fields that have the span of a granule, ~ 10^8 cm, and last about as long as a granule, ~ 300 s (Lites et al 2008; Ishikawa et al 2010; Ishikawa & Tsuneta 2010; Title et al 1989). Averaged over the EB's granule-size area, the strength of the magnetic field in an EB is ~ 100 G (Lites et al 2008). At any time, there is an EB in about 1 out of 10 granules (Lites et al 2008; Ishikawa et al 2008), or about 100 EBs per supergranule, twice our estimated number of Type-II spicules. So, EBs are small enough and numerous enough to possibly be the drivers of Type-II spicules.

3. SCENARIO

From the observations described in Section 2, and as we reason in Moore et al (2010), we think it is plausible that Type-II spicules are miniature analogues of X-ray jets, each Type-II spicule and the Alfven waves accompanying it being generated in tandem by an EB via a burst of reconnection with ambient field that reaches into the corona. If Type-II spicules and their Alfven waves are produced this way and carry enough mechanical energy into the corona to heat the corona and drive the solar wind, then EBs are likely the main engines powering the heliosphere.

This scenario for powering coronal heating and the solar wind is schematically depicted by the cartoon in Figure 2. This sketch represents the magnetic field and its activity in a vertical plane centered on a typical supergranule convection cell of diameter ~ 3 x 10^9 cm in a coronal hole having predominantly positive-polarity magnetic flux. The coronal field funnels down into the magnetic network at the edges of the cell. On each side of the cell we have an EB embedded in the edge of the network field. The EB on the left has its negative-polarity end farther inside the network field than its positive-polarity end, whereas the EB on the right has its positive-polarity end farther inside. For each of these two EBs, some prior reconnection with the network field has formed a smaller bipole just outside the negative end of the EB.

The EB on the left is undergoing a burst of reconnection with the ambient network field in the manner of a standard X-ray jet: the interior of the EB is remaining inert during this burst of reconnection. The sling-shot snapping action of the reconnected field lines produces (1) an upward jet of plasma: a Type-II spicule, (2) Alfven waves that travel up along the ambient field in and around the spicule, and (3) fast-mode MHD waves that propagate upward across the ambient field. The EB on the right is undergoing a burst of reconnection with the ambient field

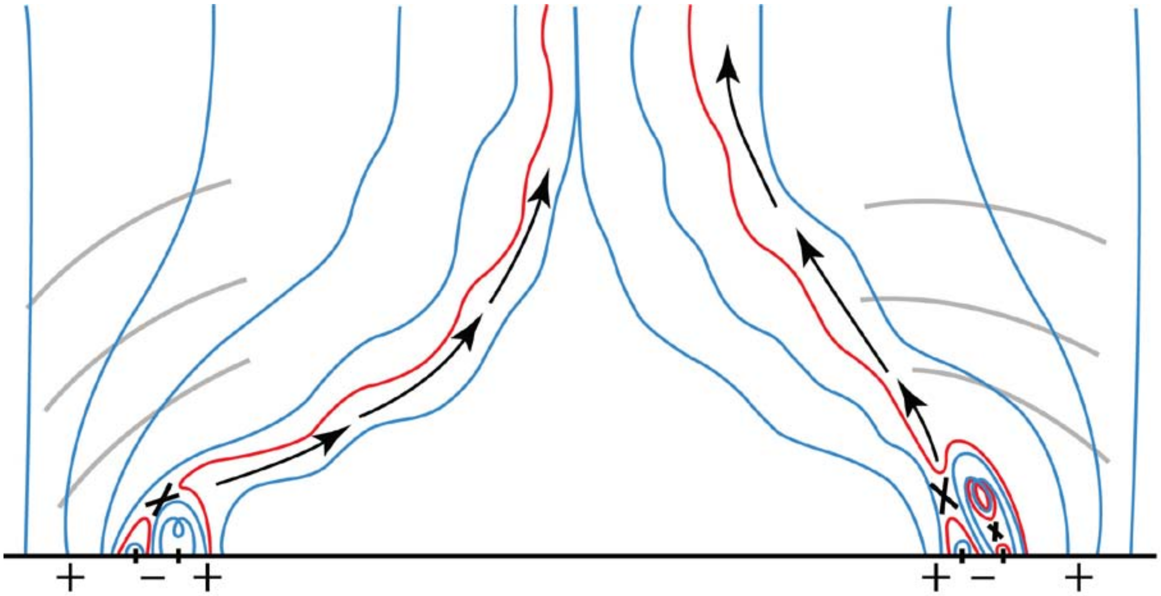

Figure 2. Larger version of the cartoon in Figure 1, depicting the production of MHD waves and Type-II spicules by EBs (after Falconer et al 2003). The thick black line is the photospheric surface. Plus and minus signs give the polarity of the magnetic flux. Black Xs symbolize magnetic reconnection. Black arrows represent Type-II spicules. Red curves are newly reconnected field lines. Blue curves are field lines that have not yet undergone reconnection or will not undergo reconnection. The wiggles in the field lines are the undulations of upward-propagating Alfven waves. The gray arcs are fast-mode MHD waves.

in the manner of a blowout X-ray jet: the interior field of the EB has enough shear and twist that it is undergoing a blowout eruption. Again, as for the event on the left side of Figure 2, the snapping action of the field lines reconnected on the outside of the erupting EB produces a Type-II spicule, Alfven waves, and fast-mode MHD waves. In addition, the erupting body of this EB acts to further generate Alfven waves and fast-mode waves as it erupts up along nearly the same path as the initial Type-II spicule shown here and becomes a complex following part of the spicule jet.

While we do expect the generation of either a standard-jet Type-II spicule or a blowout-jet Type-II spicule to generate fast-mode MHD waves, these fast-mode waves have yet to be identified in observations. In Section 4, we estimate from published observations the mechanical energy flux put into the corona by the generation of Type-II spicules if Type-II spicules are generated as in the scenario depicted in Figure 2. We obtain a conservative estimate by ignoring the fast-mode waves and estimating only the energy flux carried by Type-II spicules and their co-generated Alfven waves.

4. NON-THERMAL ENERGY FLUXES

In Table 1 are tabulated our estimates of (1) F_{mag}, the area-average flux of magnetic energy carried into the chromosphere by EBs in quiet regions and coronal holes, and (2) F_{mech}, the area-average flux of mechanical energy carried into the corona by Type-II spicules and their accompanying Alfven waves if these are generated in tandem by EBs as in Figure 2. F_{mech} is the sum of F_{kin}, F_{pot}, F_{work}, and F_A, where F_{kin}, F_{pot}, and F_{work} are respectively the area-average flux of kinetic energy, potential energy, and work energy carried by Type-II spicules, and F_A is the area-average energy flux carried by the co-generated Alfven waves. The formulas used to estimate these six non-thermal energy fluxes are given in Table 1. The physical quantities in these formulas are defined in Table 2 which also gives the empirical value adopted for each quantity and the published sources of these values. In estimating F_{kin}, F_{pot}, F_{work}, and F_A we have assumed that the density and temperature of the plasma in Type-II spicules are comparable to those in classical spicules. In estimating F_A we have assumed that the diameter of the beam of Alfven waves co-generated with a Type-II spicule is comparable to the diameter of the EB at the base of the spicule.

In agreement with a previous estimate by Bueno et al (2004), we find that $F_{mag} \sim 1 \times 10^7$ erg cm^{-2} s^{-1}, which is of the order of the non-thermal energy flux needed to heat the chromosphere in quiet regions and coronal holes (Anderson & Athay 1989). As Table 1 shows, we find that $F_{mech} \sim 7 \times 10^5$ erg cm^{-2} s^{-1}, split about half and half between Type-II spicules and the co-generated Alfven waves. Of the $\sim 4 \times 10^5$ erg cm^{-2} s^{-1} carried by Type-II spicules ($\equiv F_{kin} + F_{pot} + F_{work}$), about 75% is F_{kin}, about 25% is F_{pot}, and only a negligibly small amount is F_{work}. The value of $\sim 7 \times 10^5$ erg cm^{-2} s^{-1} for F_{mech} is comparable to the $\sim 5 \times 10^5$ erg cm^{-2} s^{-1} needed to power the coronal heating and solar wind in quiet regions and coronal holes, and hence is enough for the EBs, via generation of Type-II spicules, to be the main generators of the heliosphere.

Table 1

Non-Thermal Energy Fluxes [a]

Type of Energy Flux and Its Carrier and/or Generator	Symbol	Formula	Estimated Value (erg cm^{-2} s^{-1})
Magnetic-energy flux of EBs [b]	F_{mag}	$F_{mag} \sim (8\pi)^{-1} f_{EB} (B_{EB})^2 D_{EB} (\tau_{EB})^{-1}$	$\sim 1 \times 10^7$
Energy flux of Alfven waves generated by EBs	F_A	$F_A \sim (4\pi)^{-1/2} f_{gen} f_{EB} (\rho_{II})^{1/2} (v_{lat})^2 B$	$\sim 3 \times 10^5$
Kinetic-energy flux of Type-II spicules generated by EBs	F_{kin}	$F_{kin} \sim (1/2) f_{II} \rho_{II} (v_{II})^3$	$\sim 3 \times 10^5$
Potential-energy flux of Type-II spicules generated by EBs	F_{pot}	$F_{pot} \sim g f_{II} L_{II} \rho_{II} v_{II}$	$\sim 8 \times 10^4$
Work-energy flux of Type-II spicules generated by EBs	F_{work}	$F_{work} \sim f_{II} p_{II} v_{II}$	$\sim 1 \times 10^4$
Total mechanical-energy flux of Alfven waves and Type-II spicules generated by EBs	F_{mech}	$F_{mech} \equiv F_A + F_{kin} + F_{pot} + F_{work}$	$\sim 7 \times 10^5$

[a] Estimated area-average upward non-thermal energy fluxes due to granule-size emerging bipoles in quiet regions and coronal holes.

[b] EB denotes a granule-size emerging bipole.

Table 2

Physical Parameters [a]

Parameter	Symbol	Adopted Value	Source of Adopted Value
Area filling factor of EBs [b]	f_{EB}	~ 0.1	Lites et al (2008), Ishikawa et al (2008)
Magnetic field strength in EBs	B_{EB}	~ 100 G	Lites et al (2008)
Diameter of granules	D_G	$\sim 10^8$ cm	Title et al (1989)
Lifetime of granules	τ_G	~ 300 s	Title et al (1989)
Diameter of EBs	D_{EB}	$D_{EB} \sim D_G$ $\sim 10^8$ cm	Lites et al (2008), Ishikawa et al (2010)
Lifetime of EBs	τ_{EB}	$\tau_{EB} \sim \tau_G$ ~ 300 s	Ishikawa & Tsuneta (2010)
Fraction of their lifetime EBs spend generating Type-II spicules	f_{gen}	~ 0.5	Est. instantaneous number of Type-II spicules per EB
Plasma mass density in Type-II spicules	ρ_{II}	$\sim 3 \times 10^{-13}$ gm	Sterling (2000)
Speed of lateral motion of Type-II spicules	v_{lat}	$\sim 2 \times 10^6$ cm s^{-1}	De Pontieu et al (2007b)
Magnetic field strength in upper chrom. in quiet regions and coronal holes	B	~ 10 G	Ito et al (2010)
Diameter of Type-II spicules	D_{II}	$\sim 2 \times 10^7$ cm	De Pontieu et al (2007a)
Area filling factor of Type-II spicules	f_{II}	$\sim 2 \times 10^{-3}$	$f_{II} = f_{gen}\, f_{EB}\, (D_{II}/D_{EB})^2$
Speed of upward motion of Type-II spicules	v_{II}	$\sim 10^7$ cm s^{-1}	De Pontieu et al (2007a)
Acceleration of gravity in upper chromosphere	g	$\approx 2.7 \times 10^4$ cm s^{-2}	Allen (1973)
Length of Type-II spicules	L_{II}	$\sim 5 \times 10^8$ cm	De Pontieu et al (2007a)
Plasma temperature in Type-II spicules	T_{II}	$\sim 10^4$ K	Sterling (2000)
Plasma pressure in Type-II spicules	p_{II}	~ 0.5 dyne cm^{-2}	$p_{II} \approx 2\,(k/m_p)\,\rho_{II}\,T_{II}$ [c]

[a] The physical parameters and their values used to obtain the values of the energy fluxes in Table 1.

[b] EB denotes a granule-size emerging bipole.

[c] k is the Boltzmann constant; m_p is the proton mass.

5. DISCUSSION

Previously, De Pontieu et al (2007b) concluded from the observed Alfven-wave oscillatory motions of Type-II spicules that the Alfven waves in and around Type-II spicules carry enough energy to power coronal heating and the solar wind in quiet regions and coronal holes. They assumed that the Alfven waves that shake Type-II spicules in the upper chromosphere fill the horizontal area, and they proposed no specific scenario for the generation of these waves. Our estimate of the energy carried by Alfven waves in and around Type-II spicules roughly confirms the conclusion of De Pontieu et al (2007b), and we offer a specific observationally-based plausible scenario for how these waves are generated. In addition, from observations and our scenario, we estimate that Type-II spicules carry about as much mechanical energy into the corona as do the Alfven waves in and around them.

The observed number of EBs in quiet regions and coronal holes, the observed number of Type-II spicules, our scenario for the production of Type-II spicules by EBs, and our empirical estimate of the energy flux carried into the corona by Type-II spicules and their co-produced Alfven waves, together strongly point to EBs being the main engines of the heliosphere. However, while from the observations and our scenario it appears quiet likely that Type-II spicules and their Alfven waves are generated by EBs, it remains to be directly shown from observations that this is in fact the case. This is a crucial question to be decided by analysis of present and future coordinated observations of Type-II spicules and EBs.

From analysis of the luminosity of the EUV corona and the magnetic flux content of the underlying magnetic network in quiet regions, Falconer et al (2003) made the following prediction: "(1) transient sheared-core bipoles of the size of granules and having transverse field strengths greater than ~ 100 G will be found at the edges of network flux clumps, (2) ~ 30 of these bipoles will be found per supergranule, and (3) most spicules will be found to come from explosions of these bipoles." The *Hinode* observations of Type-II spicules and EBs and the results of this paper are in accord with this prediction. This prediction will be largely borne out if it is observed that most Type-II spicules stem from EBs.

Finally, since granular magnetoconvection evidently occurs in active regions as much or more as in the rest of the solar surface, we note that EBs produced in active regions might drive much of the coronal heating in active regions in a similar way as in quiet regions and coronal holes. This possibility is suggested by observed fine-scale upflows in the transition region and low corona in the feet of coronal loops in active regions (De Pontieu et al 2009) and by the recent modeling of coronal heating in active regions by Lionello et al (2011). Consistent with these results and our results, De Pontieu et al (2011) have found from new observations that Type-II spicules have hot coronal extensions, which they estimate provide all or most of the coronal heating in all regions of the Sun.

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