Heating of Stellar Winds

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In 1958, Eugene Parker proposed that the hot corona can provide sufficient pressure to accelerate the solar wind to become “supersonic”. While initially controversial, *in situ* measurements with US and Soviet space missions soon confirmed the solar wind’s existence. Now the wide existence of stellar winds is the conventional wisdom. Despite the universal acceptance of the concept, Parker made one big assumption, that there was a mechanism which could heat the coronal gas to 3-4 million K so that the Sun’s gravity could be counteracted and the solar wind could speed up to hundreds of kilometers per second.

In the intervening half century, the Sun has been studied in depth at various wavelengths using different methods both on ground and in space; the spacecraft have probed the outer corona to a heliocentric distance of 0.29 AU and at a wide latitudinal range within about $\pm 80^{o}$. In parallel, a raft of theoretical models has been put forward. Some traditional views of the solar wind have been changed. Now we know the fast wind (600-800 km/s), rather than the slow wind (300-500 km/s), is in fact the more “ambient” steady state of the solar wind (*e.g.*, Feldman *et al*., 1976; Axford, 1977). Instead of a simple process, many mechanisms contribute to heat the corona and accelerate the solar wind. The coronal heating mechanisms change with height from the corona base, and also differ in the regions feeding fast and slow winds.

Below about 1.5 solar radii (Rs), different combinations of mechanisms, such as magnetic reconnection, turbulence, wave dissipation, and plasma instabilities, are probably responsible for the varied appearance of coronal holes, quiet regions, isolated loops, and active regions (Priest *et al*., 2000; Aschwanden *et al*., 2001; Cargill and Klimchuk, 2004; Cranmer, 2004a). However, observations suggest that the average coronal temperatures in open magnetic regions feeding the solar wind are no greater than ~ 2 million K, and the most sophisticated solar wind models can not produce a fast wind without the deposition of heat or momentum in some form into the corona besides the gas pressure gradient (*e.g.*, Holzer and Leer, 1980). Therefore, the extended coronal heating at distances greater than about 2 Rs is necessary to generate fast wind (Leer *et al*., 1982; Parker, 1991). Based on the smaller radial gradients in proton and electron temperatures than pure adiabatic expansion (*e.g*., Phillips *et al*., 1995; Richardson *et al*., 1995), as well as the extremely high heavy ion temperatures, faster bulk ion outflow than protons, and strong anisotropies of ion velocity distributions in the extended corona (Kohl *et al*., 1997, 1998, 1999; Noci *et al*,, 1997; Li *et al*., 1998; Cranmer *et al*., 1999; Giordano *et al*., 2000), Cranmer (2002) has revealed the necessity and constraints of the extended coronal heating.

The list of proposed physical processes responsible for the extended coronal heating is limited both by the nearly collisionless nature of the plasma and by the observed temperature conditions (Cranmer, 2004a). Most suggested mechanisms involve the transfer of energy from propagating fluctuations to particles (Cranmer, 2004a). Ultimately, the energy must arise from the solar energy and through one or more processes be converted to the thermal energy of the accelerated solar wind protons. There are many clues to the answer, but no one has yet been able to correctly interpret all the clues. Acceleration favors ions with low first ionization potential. This points to processes near the Sun where there are significant neutral populations. As illustrated by Figure 1, the Ultraviolet Coronagraph Spectrometer (UVCS) on SOHO has shown that O^{5+} ions are strongly heated near 2 Rs. Surprisingly, the parallel temperature of O^{5+} ions thereafter cools while the perpendicular temperature rises (Cranmer, 2004b). Such a large temperature anisotropy could be produced by ion pickup, but it is unclear what the source of these new ions is. The plasma could be heated by ion-cyclotron waves, but if so, what is the source of the waves? We expect that any such waves in the corona would have been absorbed by cyclotron resonance with protons and helium ions before reaching 1 AU. So these waves should be invisible from our spacecraft.

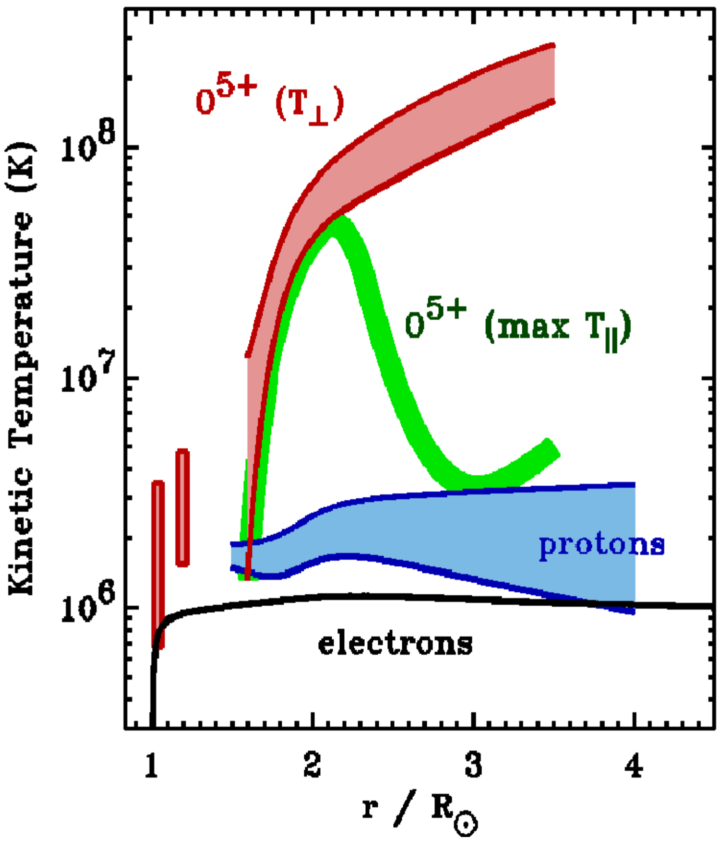

Figure 1. The radial variations of kinetic temperatures of electrons, protons, and O^{5+}, from about 1 to 4 Rs. Adopted from Cranmer (2004b).

Unexpectedly, the Helios and STEREO missions have found strong ion-cyclotron waves below the proton gyro-frequency in the plasma frame but above the proton gyro-frequency in the Doppler-shifted spacecraft frame. The field-aligned propagation direction of these waves may have allowed them to reach 0.3 and 1 AU from source regions close to the Sun. Even if these waves, as shown in Figures 2 and 3, are from the corona, we cannot tell how strong they are in the corona, what frequency range they cover in the source region, their source mechanism, and whether they have sufficient power to accelerate the solar wind.

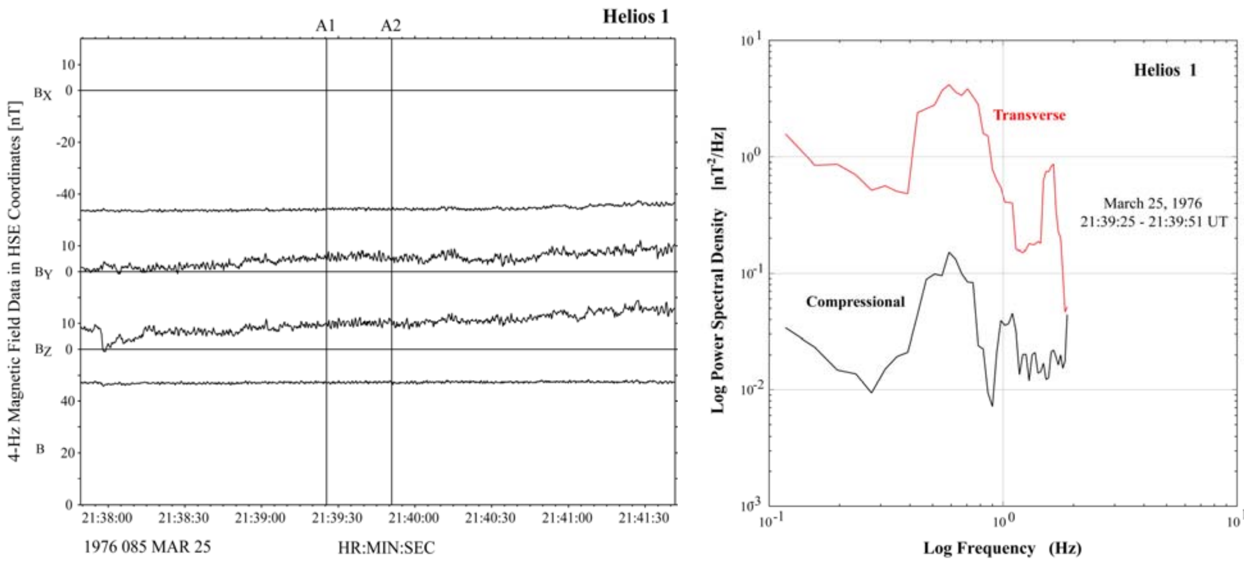

Figure 2. Example of ion cyclotron wave observed near 0.3 AU using 4-Hz magnetometer data of Helios 1 spacecraft. Left: time series of magnetic field in Helios solar ecliptic (HSE) coordinates during 21:37:50 – 21:40:40 UT on March 25, 1976. Right: the power spectral density of the wave in the interval A1-A2, which lasted 26 seconds. The transverse power (red) is 1.5 orders of magnitude higher than the compressional power (black). The wave ellipticity is -0.92, with negative indicating left-handed in spacecraft frame. The wave propagates about 6^o away from the magnetic field.

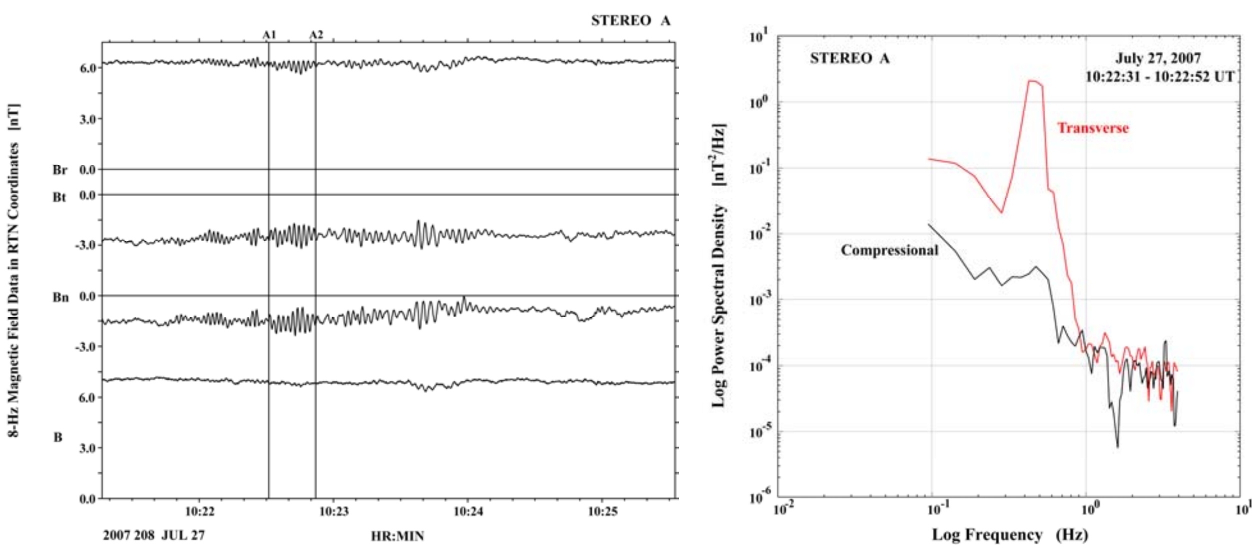

Figure 3. Example of ion cyclotron wave observed near 1 AU using 8-Hz magnetometer data of STEREO A spacecraft. Left: time series of magnetic field in RTN coordinates during 10:21:20 – 10:25:30 UT on July 27, 2007. Right: the power spectral density of the wave in the interval A1-A2, which lasted 21 seconds. The transverse power (red) is three orders of magnitude higher than the compressional power (black). The wave is almost circularly polarized wave and it propagates only 2^o away from the magnetic field.

The slow wind originates mainly from the helmet streamers. Since the helmet streamers are thought primarily closed magnetic loops or arcades, to understand how the plasma expands into a slow flow is a necessary prerequisite for studying the slow wind acceleration (Cranmer, 2004a). SOHO has shown the existence of two cases: slow wind flowing along the open-field edges of the closed regions, and the closed fields occasionally opening up and releasing plasma. Some studies have suggested that the stability of streamers may be closely related to the kinetic partitioning of heat to protons versus electrons (Endeve *et al*., 2004). Nevertheless, we still do not have an exact census of the mass and energy budget of slow wind source regions (Cranmer, 2004a).

Overall, we face different problems to solve the fast and slow wind acceleration. On the other hand, how the gas temperature increases so dramatically near the coronal base is not well understood neither. We do not know what fraction of the solar wind's mass, momentum, and energy flux is driven by Parker-type gas pressure gradients, and what fraction is driven by, *e.g.*, the wave-particle interactions or turbulence (Cranmer, 2004a).

In the coming decade, the solar physics community needs to interact more with the space physics community. A mission deep closer to the corona will be a link between the two. For example, to pursue the tantalizing glimpse into ion cyclotron waves coming from the corona as shown in Figures 2 and 3, we need to obtain *in situ* data much closer to the Sun than obtained before. We need not just appropriate wave measurements, but also a full characterization of the properties of the field and plasmas in this region.

Efforts have been made to initiate a Solar Probe mission for decades. The arguments for such a mission have only become stronger in the intervening years. All of stellar physics would benefit if we could probe the coronal region of our own star, the Sun. Moreover, the space weather prediction community would strongly benefit. At present, many solar models, such as the Wang-Sheeley-Arge model (Arge and Pizzo, 2000; Arge *et al*., 2002) and the Magnetohydrodynamics-Around-a-Sphere model (Mikić and Linker, 1994; Linker et al., 1999; Mikić et al., 1999), all use the empirical relationship to get the solar wind temperature condition, rather than any realistic coronal heating mechanism. As a result, the modeling output does not match the observations well. If we can better understand the solar wind heating, these models along with the space weather forecasting will be improved greatly. We recommend the initiation of the mission at the earliest opportunity.

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