1.2 What mechanisms heat the corona and heat and accelerate the solar wind?

Present state of knowledge:

Despite more than a half-century of study, the basic physical processes responsible for heating the million-degree corona and accelerating the solar wind are still not known. Identification of these processes is important for understanding the origins and impacts of space weather and to make progress in fundamental stellar astrophysics.

Ultimately, the problem of solar wind acceleration is a question of the transfer, storage, and dissipation of the abundant energy present in the solar convective flows. The key question is to establish how a small fraction of that energy is transformed into magnetic and thermal energy above the photosphere. Both emerging magnetic flux and the constant convective shaking and tangling of magnetic field lines already threading the corona contribute to the processing of the energy in what is an extremely structured, highly dynamic region of the solar atmosphere, the route to dissipation involving cascading turbulence, current sheet collapse and reconnection, shocks, high-frequency waves, and wave-particle interactions. The advent of high-cadence high-resolution observations has demonstrated the extremely complex phenomenology of the energy flux in the lower atmosphere, including many types of transient events discovered and classified by Yohkoh, SOHO, TRACE, RHESSI, Hinode and, most recently, SDO.

Energy deposited in the corona is lost in the form of conduction, radiation (negligible in coronal holes), gravitational enthalpy, and kinetic energy fluxes into the accelerating solar wind plasma. Transition region pressures, coronal densities and temperatures, and the asymptotic solar wind speed are sensitive functions of the mode and location of energy deposition. The mass flux is not, however, as it depends only on the amplitude of the energy flux (Hansteen and Leer 1995). A relatively constant coronal energy flux therefore explains the small variations in mass flux between slow and fast solar wind found by Ulysses during its first two orbits, although the dramatic decrease in mass flux over the last cycle points also to a decreased efficiency of coronal heating and therefore to its dependence on the solar magnetic field (McComas et al. 2008; Schwadron and McComas 2008).

One of the fundamental experimental facts that has been difficult to account for theoretically is that the fast solar wind originates in regions where the electron temperature and densities are low, while the slow solar wind comes from hotter regions of the corona. The anticorrelation of solar wind speed with electron temperature is confirmed by the anti-correlation between wind speed and ‘freezing in’ temperature of the different ionization states of heavy ions in the solar wind (Geiss et al. 1995) and implies that the electron pressure gradient does not play a major role in the acceleration of the fast wind. On the other hand, the speed of the solar wind is positively correlated with the in-situ proton temperature, and the fastest and least collisionally coupled wind streams also contain the largest distribution function anisotropies. Observations of the very high temperatures and anisotropies of coronal heavy ions suggest that other processes such as magnetic mirror and wave-particle interactions should also contribute strongly to the expansion of the fast wind (Li et al. 1998; Kohl et al. 1997, 1998, 2006; Dodero et al. 1998). In particular, either the direct generation of high-frequency waves close to the cyclotron resonance of ions or the turbulent cascade of energy to those frequencies should play an important role.

Theoretical attempts to develop self-consistent models of fast solar wind acceleration have followed two somewhat different paths. First, there are models in which the convection-driven jostling of magnetic flux tubes in the photosphere drives wave-like fluctuations that propagate up into the extended corona. The waves partially reflect back toward the Sun, develop into strong turbulence, and/or dissipate over a range of heights. These models also tend to attribute the differences between the fast and slow solar wind not to any major differences in the lower boundary conditions, but to the varying expansion factor of magnetic field lines in different areas of coronal holes (Cranmer et al. 2007).

In the second class of models, the interchange reconnection models, the energy flux usually results from magnetic reconnection between closed, loop-like magnetic flux systems (which are in the process of emerging, fragmenting, and being otherwise jostled by convection) and the open flux tubes that connect to the solar wind. Here the differences between fast and slow solar wind result from qualitatively different rates of flux emergence, reconnection, and coronal heating in different regions on the Sun (Axford and McKenzie 1992; Fisk et al. 1999; Schwadron and McComas, 2003).

It has been difficult to evaluate competing models of fast wind acceleration and to assess observationally the relative contributions of locally emerging magnetic fields and waves to the heat input and pressure required to accelerate the wind largely because of the absence of measurements of the solar wind close to the Sun where they can be mapped with sufficient precision to a solar source region.

How Solar Orbiter will address this question:

Solar Orbiter’s combination of high-resolution measurements of the photospheric magnetic field together with images and spectra at unprecedented spatial resolution will make it possible to identify plasma processes such as reconnection/shock formation and wave dissipation in rapidly varying surface features, observe Doppler shifts of the generated upflows, and determine compositional signatures. Whatever the scale, magnetic reconnection leads to particle dissipative heating and acceleration and wave generation, which have the net effect of a local kinetic energy increase in the lower solar atmosphere that can be revealed through high-resolution extreme ultraviolet (EUV) imaging and spectroscopy. Wave propagation will be traced from the source site to the region of dissipation through observations of EUV-line broadening and Doppler shifts.

Global maps of the H outflow velocity, obtained by applying the Doppler dimming technique to the resonantly scattered component of the most intense emission line of the outer corona (H I 121.6), will provide the contours of the maximum coronal expansion velocity gradient for the major component of the solar wind, and the role of high-frequency cyclotron waves will be comprehensively assessed by measuring spectroscopically the particle velocity distribution across the field and determining the height where the maximum gradient of outflow velocity occurs (Telloni et al. 2007).

Solar Orbiter’s heliospheric imager will measure the velocity, acceleration, and mass density of structures in the accelerating wind, allowing precise comparison with the different acceleration profiles of turbulence- driven and interchange reconnection-driven solar wind models.

As it is performing imaging and spectroscopic observations of the corona and photosphere, Solar Orbiter will simultaneously measure in situ the properties of the solar wind emanating from the source regions. The in-situ instrumentation will determine all of the properties predicted by solar wind acceleration models: speed, mass flux, composition, charge states, and wave amplitudes. Moving relatively slowly over the solar surface near perihelion, Solar Orbiter will measure how properties of the solar wind vary depending on the changing properties of its source region, as a function of both space and time, distinguishing between competing models of solar wind generation.

Detailed sub-objectives:

- 1.2.1 What mechanisms heat the corona?
  - 1.2.1.1 Energy flux in the lower atmosphere
  - 1.2.1.2 Energy and mass flux in the corona.
  - 1.2.1.3 Contribution of flare-like events on all scales
  - 1.2.1.4 Observe and explore flare-like ‘heating events’ from the quiet corona
  - 1.2.1.5 Determine whether coronal heating is spatially localized or uniform, and time steady or transient or impulsive for a wide range of magnetic loops with different spatial scales.
  - 1.2.1.6 Resolve the geometry of fine elemental loop strands
  - 1.2.1.7 Detect and characterise waves in closed and open structures
  - 1.2.1.8 Investigate the role of small scale magnetic flux emergence in energizing the above laying layers
  - 1.2.1.9 Multi-temperature diagnostics of flaring coronal loops
  - 1.2.1.10 Heating in flaring loops vs heating in active regions
- 1.2.2 What mechanisms heat and accelerate the solar wind?
  - 1.2.2.1 Determine where energy is deposited in the solar wind
  - 1.2.2.2 What drives the evolution of the solar wind distribution functions in situ?
  - 1.2.2.3 What is the nature and origin of waves, turbulence and small-scale structures?
  - 1.2.2.4 Solar wind reconnection physics
  - 1.2.2.5 Magnetic reconnection in the chromosphere, the transition region and the corona
  - 1.2.2.6 Study fast plasma flows from the edges of solar active regions discovered with Hinode/EIS
  - 1.2.2.7 Study the correlation degree between velocity and magnetic field fluctuations in the interplanetary space
  - 1.2.2.8 What determines the azimuthal flow of the near-Sun solar wind?