2.3 How and where do shocks form in the corona and in the heliosphere?

Present state of knowledge:

The rapid expulsion of material during CMEs can drive shock waves in the corona and heliosphere. Shocks in the lower corona can also be driven by flares, and in the case of CME/eruptive flare events, it may be difficult to unambiguously identify the driver (Vršnak and Cliver 2008). CME-driven shocks are of particular interest because of the central role they play in accelerating coronal and solar wind particles to very high energies in SEP events.

Shocks form when the speed of the driver is super-Alfvénic. The formation and evolution of shocks in the corona and the inner heliosphere thus depend (1) on the speed of the driving CME and (2) on the Alfvén speed of the ambient plasma and its spatial and temporal variations. According to one model of the radial distribution of the Alfvén speed in the corona near active regions, for example, shocks can form essentially in two locations, in the middle corona (1.2-3 RSun), where there is an Alfvén speed minimum, and distances beyond an Alfvén speed maximum at ~4 RSun (Mann et al. 2003). A recent study of CMEs with and without type II radio bursts (indicative of shock formation) has shown that some of the fast and wide CMEs observed produced no shock or only a weak shock because they propagated through tenuous regions in the corona where the Alfvén velocity exceeded that of the CME (Gopalswamy et al. 2008). CME shock formation/evolution can also be affected by the interaction between an older, slower-moving CME and a faster CME that overtakes it. Depending on the Alfvén speed in the former, the interaction may result in the strengthening or weakening of an existing shock driven by the overtaking CME or, if there is no existing shock, the formation of one (Gopalswamy 2001; 2002).

Studies of LASCO images obtained during the rising phase of solar cycle 23 have demonstrated the feasibility of detecting CME-driven shocks from a few to ~20 RSun and of measuring their density compression ratio and propagation direction (Vourlidas et al. 2003; Ontiveros and Vourlidas 2009). This development has opened the way for the investigation of shock formation and evolution in the lower corona and heliosphere through Solar Orbiter’s combination of remote-sensing observations and in-situ measurements.

How Solar Orbiter will address this question:

Understanding shock generation and evolution in the inner heliosphere requires knowledge of the spatial distribution and temporal variation of plasma parameters (density, temperature, and magnetic eld) throughout the corona. Solar Orbiter’s remote-sensing measurements – in particular electron density maps derived from the polarized visible-light images and maps of the density and outflow velocity of coronal hydrogen and helium – will provide much improved basic plasma models of the corona, so that the Alfvén speed and magnetic field direction can be reconstructed over the distance range from the Sun to the spacecraft. Remote sensing will also provide observations of shock drivers, such as flares (location, intensity, thermal/non-thermal electron populations, time-profiles), and manifestations of CMEs (waves, dimmings, etc.) in the low corona with a spatial resolution of a few hundred kilometers and cadence of a few seconds. It will measure the acceleration profile of the latter and then track the CMEs through the crucial heights for shock formation (2-10 RSun) and provide speed, acceleration, and shock compression ratio measurements.

Type II bursts, detected by Solar Orbiter, will indicate shock-accelerated electron beams produced by the passage of a CME and thus provide warning of an approaching shock to the in-situ instruments. These in-situ plasma and magnetic field measurements will fully characterize the upstream and downstream plasma and magnetic field properties and quantify their microphysical properties, such as turbulence levels and transient electric fields (while also directly measuring any SEPs). Spacecraft potential measurements also allow for rapid determinations of the plasma density, and of electric and magnetic field fluctuations, on microphysical scales, comparable to the Doppler-shifted ion scales, which are characteristic of the spatial scales of shocks. The evolution of such parameters will provide insight into the processes dissipating shock fronts throughout the range of magnetic/velocity/density and pressure parameter space. Because of Solar Orbiter’s close proximity to the Sun, the measurements of the solar wind plasma, electric field, and magnetic field will be unspoiled by the dynamical wind interaction pressure effects due to solar rotation and will provide the first reliable data on the magnetosonic speed, the spatial variation of the plasma pressure and magnetic field in the inner heliosphere. MHD modeling studies have shown that interactions among recurring CMEs and their shocks occur typically in the distance range around 0.2-0.5 AU (Lugaz et al. 2005). Solar Orbiter will spend significant time in the regions of recurring CME interactions and so will be able to investigate the effects of such interactions on the evolution of CME-driven shocks.

Detailed sub-objectives:

- 2.3.1 Coronal shocks
- 2.3.2 What are the properties and distribution of heliospheric shocks?
    - 2.3.2.1 Understand coronal conditions under which the shocks form and determine the interplanetary conditions where they evolve
    - 2.3.2.2 Identify interplanetary shocks and characterise their spatial and temporal evolution
    - 2.3.2.3 Study heating and dissipation mechanisms at shocks with radial distance
    - 2.3.2.4 Identify mechanisms that heat the thermal solar wind particle populations near shocks and determine their energy partition
- 2.3.3 Resolve the interplanetary shock field and plasma structure down to the spatial and temporal scales comparable and smaller than the typical ion scales.
- 2.3.4 Shock-surfing acceleration mechanism
- 2.3.5 Understand the radio emissions from the ICME driven shocks
- 2.3.6 Identify shock accelerated particles