Coronal hole plumes

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Plumes are ubiquitous ray-like structures in coronal holes, extending up to many solar radii above the limb. It is thought that plumes trace the open field lines emerging from the coronal holes. Plumes are stable structures normally lasting days. As shown by Ulysses and SOHO, during solar minimum coronal holes occupy most of the heliosphere, down to 25 degrees of latitude. Line-of-sight measurements of line shifts with SOHO/SUMER suggest outflow speeds of the order of 10-20 km/s at the base of the coronal holes (see, e.g. Wilhelm et al 2000, A&A, 353, 749), and very small at the base of polar plumes, but measurements have been difficult due to the fact that most plumes are close to the plane of the sky. Doppler dimming techniques applied to SOHO/SUMER and UVCS spectra taken at larger heights have produced contradictory results (see, e.g. Gabriel et al. 2003, ApJ, 589, 623), with outflows speeds of the order of 60 km/s attributed to either plume or inter-plume regions by different authors. Clearly, direct and accurate measurements of line shifts and profiles out of the ecliptic are needed.
Quasi-periodic 10-minutes fluctuations in intensity have been observed in plumes (cf. DeForest and Gurman 1998, ApJL, 501, L217) and have been interpreted as slow magnetoacustic waves propagating at 75-150 km/s. Other authors have found signatures of waves in the inter-plume regions as well.
SOHO measurements have indicated that plumes are slightly denser and cooler than the surrounding regions. Also, that elemental abundances are close to photospheric, despite previous thoughts (see Del Zanna et al. 2003, A&A, 398, 743 for details).

The formation of plumes might be related to magnetic reconnection processes occurring in the low atmosphere, but the limitations of magnetic measurements near the poles have precluded conclusive evidence.

In summary it is still not clear: a) if plumes are the main sources of the fast wind observed at 1 AU; b) what are the acceleration mechanisms and what is the role of the observed waves. Close-by in-situ measurements, coupled with remote-sensing spectroscopic measurements of the source regions are needed. Solar Orbiter can solve these outstanding problems with its unique capabilities:

(a) Linking with the in-situ measurements

Plumes are stable light beams pointing out in the heliosphere, therefore are perhaps the best opportunity to link remote sensing with close-by in-situ data, considering that at the Solar Orbiter distance the particles are still frozen in the magnetic field.

(b) Close-up view-point

Attempts have been made in the past with Ulysses to find traces of coronal plumes in the solar wind data, but no conclusive evidence was found (Poletto et al. 1996 A&A, 316, 374). The

fast solar wind, at large distances, appears very homogeneous. The same is not true at the close-up distances (45 solar radii) that Solar Orbiter will reach.
Indeed Thieme et al (1989, Advances in Space Research, 9, 127; 1990,Annales Geophysicae, 8, 713) have reported Helios observations of pressure-balance structures clearly present between 0.3 and 0.7 AU, with angular widths ranging between 2 and 6 degrees. Solar Orbiter will have the unique opportunity to relate these pressure-balance structures to the solar plumes visible in the lower corona and to study the interaction between plume and inter-plume regions in great detail.
A further evidence that ray-like structures in coronal holes extend to great heights was given by DeForest et al (2001, ApJ, 546, 569), who used SOHO/LASCO coronagraph images to trace the brightest plumes up to radial distances of 45 solar radii.

The close-up view-point will also directly provide a gain of a factor of at least 7 in spatial resolution, which will be fundamental in order to clearly separate the plume and inter-plume region by reducing the line-of-sight effects (which are currently dominant).
Also, we will be able to study the plumes internal structure, that current observations suggest being filamentary.
Plumes at their base have widths of the order of 10 000 km, hence spatial resolutions of the order of 100 km will provide great detail of their internal structure.

(c) Co-rotation

Ulysses was unable to relate in-situ measurements in coronal holes with the source regions because it was too far and because solar rotation strongly modulated and confused the signal during the fast polar fly-byes. Solar Orbiter, with its unique opportunity of near co-rotation, will provide day-long in-situ measurements of solar wind streaming from the same location on the Sun. Solar Orbiter is bound to observe regions that are related to plume and inter-plume regions. During the early phase of the mission the co-rotation will be the main unique advantage of Solar Orbiter to study equatorial coronal holes.

(d) Out of ecliptic view

It is essential to perform measurements from out of the ecliptic to study coronal holes and the fast wind during solar minimum. In particular in order to provide measurements of flows along the plumes, and of magnetic fields at their base.

EUS instrument requirements

1. Emission line requirements

The EUS needs to observe lines formed at 0.7-0.9 MK, i.e. in the upper transition region, where the plume bases have their peak emission (Del Zanna et al. et al. 2003, A&A, 398, 743). Lines such as Mg VIII 430, Mg IX 368, Ne VII 465, Ne VIII 780 A are good candidates. Direct temperature and density diagnostics would be necessary in order to characterise the plumes. Good temperature diagnostic is offered by the 706-749 A lines of Mg IX. Band 6 seems the best choice for primary spectral range, with strong Ne VIII lines for line shifts/profiles, good temperature diagnostic from Mg IX, and good density diagnostic in the lower TR from O V. A real plus would be the presence of second order lines, as in the SOHO/GIS (see Del Zanna et al. 2001, A&A 379, 708 for details). This would add many extra density diagnostics at coronal temperatures (e.g. Si IX, Si X), and good temperature coverage, spanning from O II 718 A (first order) to Fe XVI 360 A (second order). The extension to higher temperatures is important, since plumes at times undergo heating processes that increase their temperature at the base to a few million degrees. If not, or in addition to a second order, this could be achieved with a second band. Band 1 would be an option, but a band covering the 400-470 A would add density diagnostic from Mg VIII (430/436 A), as well as study the Mg/Ne abundance ratio with lines from Ne VI, Ne VII, Mg VI, Mg VII, Mg VIII. This would allow to study the FIP effect in plumes, and relate it to the chemical abundances measured in-situ.

2. Spectral resolution requirements

Need to measure line shifts of 1-3 km/s. If a second-order option for band 6 is chosen, the resolution must be high enough also to clearly separate the orders. Standard sampling of line profiles is sufficient.

3. Spatial coverage

A large FOV that covers a few super-granular cells (and plumes) will be essential in order to make sure that the in-situ measurements can be mapped to the right source region. An alternatively good option would be to have a smaller FOV but a good area coverage provided by the imager.

4. Time resolution (incl. count rates)

A time resolution of the order of 10s in 1-2 of the stronger lines would be needed to study waves. This could be achieved in a sit-and-stare mode. For measurements of densities, temperatures and elemental abundances the constraints are not very tight, considering how stable plume bases are. Exposures of 1-10 minutes are acceptable with rastering a large area over an hour or so. For measurements of line shifts and profiles, 100 counts/pixel will be needed.

5. Requirements for other instruments

1) In-situ measurements (densities, velocities, magnetic fields, particle distribution functions, and ion compositions) are essential.
2) An imager with a large field of view (100 000 km) that covers a few super-granular cells (and plumes) in an upper-transition region line such as Fe IX 171 A would be essential. This is to make sure that the in-situ measurements can be mapped to the right source region observed by the spectrometer.
3) Magnetograms with spatial resolutions of 500 km or better will clarify the importance of magnetic reconnection at the base of the plumes and will be key to understand which heating processes dominate at the plume bases.

6. Other requirements

The possibility to telemeter to the ground a sample dataset first, with the option to choose which data to telemeter.

Relation to Solar Orbiter science goals

1. Determine the properties, dynamics and interactions of plasma, fields and particles in the near-Sun heliosphere

Knowing the properties of the low corona will help to understand which processes might take place before the plasma is measured in-situ. In particular, which interactions between the plume and interplume regions are occurring.

2. Investigate the links between the solar surface, corona and inner heliosphere

This study will clearly provide the link between the processes in the photosphere, those in the transition region, where the plumes are the dominant features in coronal holes, and the in-situ measurement. It will enable to identify the source regions of the fast solar wind, and the role of waves in the plumes.

3. Explore, at all latitudes, the energetics, dynamics and fine-scale structure of the Sun's magnetized atmosphere

During its high-latitude passages, we will be able to study the fine-scale structures in the poles from a vantage point, and clearly trace the magnetic field lines, frozen in the plumes.

4. Probe the solar dynamo by observing the Sun's high-latitude field, flows and seismic waves

N/A