Chapter 8

8. Concluding discussion and future work

8.1 Chapter Summary

In this chapter concluding discussions are made for each of the results chapters and outstanding questions are discussed. Details are also provided of new developments and technological availability, which may be exploited to address such questions in the future.

8.2 Simultaneous IPS and STEREO Heliospheric Imager observations of a CIR

Co-rotating interaction regions play a significant role in shaping the large scale dynamics of the solar wind. In Chapter 5, a joint analysis of such a feature using both IPS and STEREO data from April 2007 is made. Velocities obtained from modelled IPS scattering, from modelling the propagation of the CIR across the heliosphere, and its subsequent detection in situ at Venus were found to be in good agreement.

The combination of IPS and wide angle heliospheric imaging allows a more rigorous interpretation of the behaviour of CIRs to be made. In Chapter 5, this has resulted in the detection of a small scale transient feature occupying some portion of the IPS raypath at the same time as the CIR. The presence of this feature was inferred from significant anti-correlation that appeared in the cross-correlation profile from the IPS data on 25 April. Additionally, the transient was observed directly by HI-1A crossing the IPS raypath at precisely the time of the IPS observations, unambiguously linking the two observations.

It is suggested that this transient feature became trapped by the magnetic field lines of the CIR and traversed the heliosphere along with it. Such an interpretation can only be made confidently as a result of the use of both techniques. IPS can detect small scale transient features, which may be below the resolution (spatial and temporal) of HI. However, the HI instrument was crucial in establishing that the CIR and transient detections in the IPS observations were not simply as a result of a CME crossing the raypath (as none was present at the time), but was as a result of a considerably more complex scenario.

The appearance of the CIR was also detected in situ, by the ASPERA-4 instrument on Venus Express. This is important because the developing compression region observed in HI (particularly HI-2A) appeared to fade as it

propagated outwards. This was not as a result of the compression region dissipating, but rather it was moving away from the Thomson sphere of the HI instrument and hence the viewing geometry became unfavourable. The in situ detection at Venus confirms that the material in the CIR did not simply dissipate but the disappearance was ultimately due to an optical effect.

Finally, the region under observation at this time was known to be highly populated by small scale transient features – the solar wind was not in an ambient state. These features were observed both in HI and IPS data and are interpreted as being responsible for significant dynamics observed in the tail of comet Encke which happened to be in the HI-1A field of view at the time. Further studies into the nature of the interactions between comet tails and the non-ambient solar wind at interplanetary distances are now both possible and highly desirable (e.g. Kellett et al., in preparation, 2009).

Further analysis of the in situ characteristics of the CIR, from the Venus Express data, and the motions of the tail of comet Encke are intended for future consideration.

8.3 Simultaneous IPS and Heliospheric Imager observations of a CME

Chapter 6 details the first joint observations of a CME using IPS and STEREO HI, at interplanetary distances. The IPS raypath, with which the CME detection was made, was found to intersect the HI-1A field of view. Strong transient features in the IPS data were found to coincide with the presence of complex small scale structures observed at the leading edge of the CME intersecting the mapped position of the IPS raypath. This is particularly evidenced by the rapid variation in plane-of-sky velocity observed in IPS. The solar wind velocity was found to increase by approximately 100kms^{-1} over just 10 minutes (Figure 6.6, middle right panel).

It is possible, in fact, that what was actually observed was a process of CME cannibalisation. A small fast transient feature in the HI-1A data was found to catch up with and merge with a slower feature. The details of how both techniques are used together are discussed in Chapter 4. The impact of the CME at Venus was also detected directly by the ASPERA-4 instrument on the Venus Express spacecraft.

This is the first time that all these data sources have been used to make a joint observation of a Venus directed CME.

The STEREO spacecraft, at the time of writing, have an angular separation of approximately 90°. The Heliospheric Imagers are now in a position that enables the 3-dimensional reconstruction of large scale solar wind features to be made from the data. This is the first time that such a capability has been available and offers much potential for analysis of the true 3-dimensional structure of features such as those described here.

The ability of IPS and in situ data to provide information on the small scale structure of these phenomena will allow 3-d models to be tested against real data. Further, the impact of such features on other planets, like Venus, can now be observed in a truly solar system wide context. Studies such as these are also likely to provoke further discussion on what is meant by the term “coronal mass ejection” as significant ambiguities are observable which frustrate easy categorisation.

8.4 Off radial flow characteristics of the fast solar wind

The purpose of Chapter 7 was to challenge the hypothesis that the fast solar wind flow is radial. Extremely long baseline IPS observations were made in 2002, 2004, 2005 and 2006 which did not result in any detection of significant off radial flow in the ambient fast solar wind. Radio sources were used such that observations could be made over both solar hemispheres, at different plane of sky heliocentric distances and at different times in the solar cycle.

Significant off radial flow characteristics were detected in the presence of an Earth directed CME in the 2005 data. A mean off radial flow of 2.38° with a standard deviation of ±1.81° was observed with separate antenna pairs. Strongly off radial flow, of up to 12° was also detected in the presence of a possible CIR on 13 May 2005. The appearance of such features demonstrates the capability of this technique to detect off radial flow when it is actually present. This is important as it reinforces the hypothesis that the fast solar wind flow is indeed radial when unperturbed, down to the detection threshold of this technique.

Numerous questions remain, that can be addressed by future long baseline IPS observations. To date, the longest projected radial baselines that have been

utilised are of the order of 2500 km. The antennas used were from the MERLIN facility in the UK and the EISCAT Svalbard Radar (e.g. Bisi et al., 2007). With increasing baseline length, the ability to record cross-correlation between received signals drops. This is due to the temporal and spatial evolution of the solar wind irregularity features that induce the phase variations. The greater the distance that the feature must traverse between the two raypaths, the more it will evolve resulting in a lower level of cross-correlation between the two observation sites. At some point the cross-correlation level will drop below the noise floor. Knowledge of the projected radial baseline length at which this takes place will enable the density irregularity decay timescales to be assessed. An increase in sensitivity of the long baseline technique will also enable further challenges to the hypothesis of radial fast solar wind flow to be made.

The new Low Frequency Array (e.g. Hessels et al., 2009) being constructed across Western Europe offers significant opportunities for IPS. The LOFAR array will consist of many networked omni-directional antennas spread across the UK, France, Holland, Germany, Denmark and Sweden. This facility provides wide angle continuous radio observation of the sky and as such can observe many natural radio sources simultaneously.

8.5 Unusual solar minimum?

A potentially interesting phenomena is occurring at the time of writing of this thesis which is that the latest solar minimum appears to be unusually extended in time. Solar activity has been essentially at solar minimum conditions from the middle of 2007 until now (early 2009). Sunspot number predictions have been revised to account for this phenomena and the dates for the next solar maximum have also been pushed back. Figure 8.1 shows the actual sunspot number and predictions for the onset of the next solar cycle. This data set was produced in April 2007 and solar maximum (for the high activity cycle) is predicted for the end of 2011.

Figure 8.2 shows a similar data set with associated predictions, produced in January 2009. As can be seen, the sunspot number has remained at virtually zero since the beginning of solar minimum in 2007. Activity during the rising phase of solar cycle 24 appears to be heavily subdued at this time. It is not yet clear whether

the Sun is entering an unusual period of solar minimum, like the Maunder minimum, as these unusual conditions have only persisted for a couple of years.

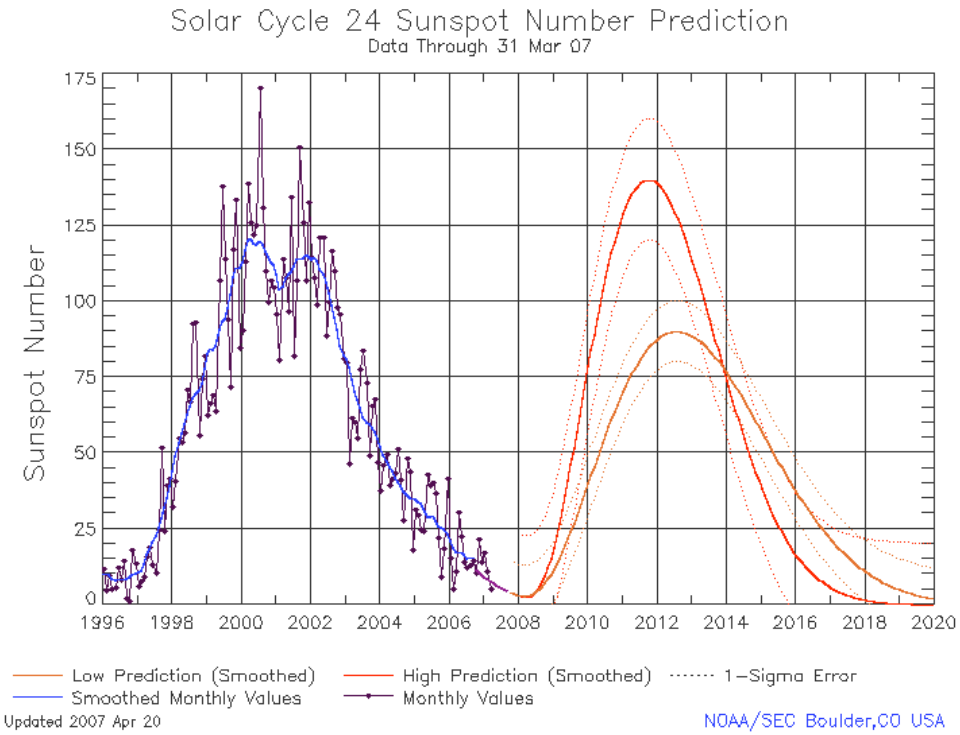

Figure 8.1 shows the sunspot number and predictions for a low and high activity solar cycle 24 as of April 2007. Solar maximum for cycle 24 for the high activity prediction is expected to occur late in 2011. (Image from NOAA website)

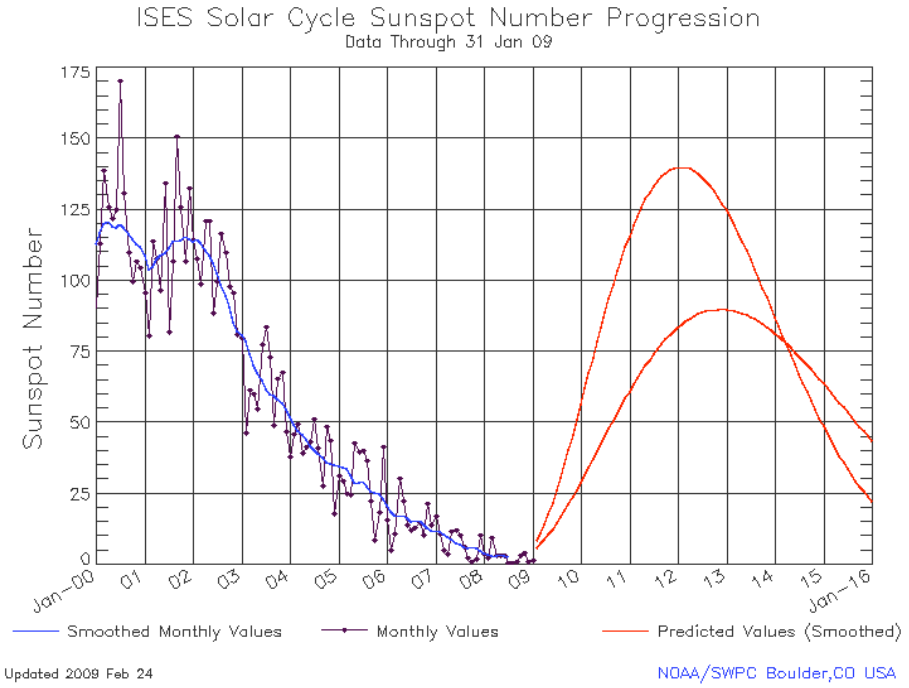

Figure 8.2 shows the sunspot number and predictions for solar cycle 24 as of February 2009. Solar minimum conditions have persisted throughout the period from 2007 to 2009 and current sunspot

number (March 2009) is observed to be well below even the low activity prediction from Figure 8.1 and still significantly below the revised prediction here. Solar maximum at this time, for the high activity cycle, has been revised back to early 2012 instead of late 2011. (Image from NOAA website)

It maybe that this is just a short term anomaly and that solar activity will return to normal in the near future. In either case, the availability of solar and heliospheric observatories and other data sources will provide the greatest capability to date with which to observed such behaviour.

8.6 Summary

The science undertaken in this thesis demonstrates the enormous potential for studying solar wind structures that results joint observations at different spatial and temporal scales. The capabilities provided by IPS and HI, coupled with in situ observations, enhanced our ability to interpret complex behaviour within large scale solar wind structures in interplanetary space. It is important, as the next (and possibly unusual) solar cycle begins, to be able to maintain and improve these capabilities where possible. These studies could not have been undertaken without the availability of the EISCAT and MERLIN radar facilities, the HI instruments on STEREO or the ASPERA-4 instrument on the Venus Express spacecraft. It is hoped that the future availability of these facilities can be assured, as their loss would represent a significant impediment to research in solar system physics.