Chapter 8

Conclusions

IPS tomography of the inner heliosphere offers an opportunity to reconstruct the average large scale distribution of Solar Wind. In spite of the fact that a successful tomographic reconstruction can yield valuable information which is not obtainable by any other means, the complexity of the problem and the lack of suitable datasets have led to there being few such attempts. The only other attempts at IPS tomography have been by the UCSD and the STELab groups who have used the index values, g, from the Cambridge 81.5 MHz telescope and the velocities from Nagoya multi-station observations at 327 MHz.

8.1 Tomographic reconstruction of the Solar Wind

8.1.1 Formulation of the problem

We formulate the problem in terms of a χ^2 minimisation exercise with the observed power spectra as the constraints for the reconstruction process and the distribution of the physical properties of the Solar Wind (velocity and C_n^2) on a fiducial surface as the free parameters of the model. The χ^2 minimisation is expected to lead to a best fit surface distribution most consistent with the observations. Earlier attempts at tomography of the Solar Wind (Jackson et al., 1998; Kojima et al., 1998; Asai et al., 1998) have used the IPS velocities estimated using the cross-correlation analysis obtained from the multi-station IPS observations as the constraints for the reconstruction procedure. The process of assigning a single velocity to the Solar Wind along a *l.o.s.* loses the information of the distribution of Solar Wind properties along the *l.o.s.* which is contained in the shape of the cross-correlation function (CCF) between different stations. The velocities obtained from such analysis are not assured to be the appropriate *l.o.s.* integrated velocities and their use is fraught with unspecifiable systematics. Our approach does not suffer from such drawbacks as we use the true observables of IPS (power spectra), which are the appropriate *l.o.s.* integrated measure of the distribution of Solar Wind properties, as the constraints for the reconstruction process and do not involve any interpretation in terms of unsuitable Solar Wind models.

8.1.2 Simulations

Our formulation of the problem of tomographic reconstruction increased the complexity of the problem many fold over the previous attempts as rather than model only two numbers (velocity and g) for each observation, it required us to model the entire power spectra and reproduce its area and shape. Since such a formulation of the problem had not been used before, we did an extensive set of simulations to validate the software developed and convince ourselves of the viability of the formulation. Another aim of the simulations was to check if the sampling of the heliosphere provided by our observations was sufficient for a reliable reconstruction. The results from our simulations show that this formulation is able to reconstruct the true structure of the Solar Wind models to a satisfactory level for data which satisfied the assumptions made by the reconstruction process. The simulations were tested for effects of noise due to measurement uncertainty in the power spectra and were not found to be seriously affected by it. Stability of the reconstructions to perturbations to the starting point for the reconstruction process was also tested and they were found to be stable to such perturbations. These simulations were used to arrive at useful estimates of the contributions of various sources of errors and uncertainties to the χ^2_G for the global Solar Wind model fit.

8.2 Observations and analysis

8.2.1 The data-set

An extensive set of IPS observations with a good coverage of the equatorial belt on the Sun was made using the Ooty Radio Telescope, India (ORT) at 327 MHz. The data comprises of 5,418 observations of individual scintillating sources and calibrators, spans $\sim$ 5 Carrington rotations and used $\sim$ 1,500 hrs of telescope time. The observed sources were selected from the list of known scintillators which has been built up at the ORT over the years. Most of the observations were confined to a heliographic latitude range of $\pm 15°$ and an elongation range of $20°$–$80°$. The epoch of observation was close to the minima of the solar activity cycle (April to August 1997) and overlaps with Carrington rotations 1921–1925. This data-set has been used for tomographic reconstruction of the Solar Wind using our formulation.

8.2.2 Automated best fit uniform Solar Wind model estimation

One of the achievements of this work has been to develop an automated procedure for estimating the best fit uniform Solar Wind models for the observed power spectra and demonstrate its effectiveness. The task of 'fitting' the spectra has traditionally been done by visual examination. It is a rather tedious exercise and allows the possibility of human errors and biases creeping in as it is difficult to maintain similar levels of objectivity while handling large databases. The automated procedure, on the other hand, provides a uniform objective criterion for fitting the spectra and relieves the astronomers of considerable drudgery. Often, when IPS is used to study the IPDs, only the disturbed spectra, which are a small fraction of the total number of observed power spectra, are of interest. This procedure provides an efficient means for picking out such observations as the IPDs spectra are expected to have significant departures from the uniform Solar Wind and therefore have poorer fits or large χ^2. The procedure thus provides a very useful tool for analysing large databases and forms an integral part of the simulations mentioned above.

8.2.3 Results of tomographic reconstruction

While the simulations lead to stable reconstructions, we found that reconstructions using the observed power spectra were not so stable. Though there were some broad similarities between different reconstructions for the same Carrington rotation which started from different starting simplexes, there were also significant differences between them. Most of the reconstructions had similar values for the final global χ^2 and therefore they all seem equally believable according to the χ^2 criteria. While comparison of the reconstructions with Solar Wind velocity measured by WIND did show some correlations, those with white light coronograph synoptic maps from LASCO-SOHO did not show any obvious correlations. The considerable difference in the nature of these measurements and IPS tomographic reconstruction should be borne in mind while making these comparisons.

The failure of our formulation to achieve convincing unique solutions with real data imply that some of the tomography assumptions are not valid and there are considerable differences in the χ^2 landscape for the observed and the simulated data. The fact that the simulated data are insensitive to perturbations of the starting point of the reconstruction process suggests the presence of a global minima which the minimisation process descends into. Of course, because of the noise associated with the reconstruction process itself, the reconstruction differs from the true model by some amount, but all the different reconstructions tend to approach the true model. The multiplicity of local minima for observed power spectra suggests that there are basic differences between the simulated and observed data. A strong indicator of the difference is that the global χ^2 for the initial guess and the final reconstruction is more than an order of magnitude larger for the observed power spectra than that for the simulations The most likely reason for the differences is that while the data for simulations was 'manufactured' to satisfy all the assumption, the observed data does not adhere to these assumptions.

The assumption of little or no time evolution during the course of a solar rotation is a rather demanding one. Though the our period of observations was close to the minima of solar activity cycle and would qualify as a 'quite' period according to most criteria, we believe that significant time evolution took place during the course of a Carrington rotation. While slow time evolution leads to the data-set being rendered inconsistent for a tomographic reconstruction, the transients act like noise in the data. If the χ^2 due to these effects is comparable to or larger than the χ^2 due to the time invariant features, the final χ^2 landscape may lead to a unique reconstruction, besides the reconstruction arrived at may not reflect the true average structure of the Solar Wind. The lack of stability of our reconstructions should be interpreted as indicative of existence of non-unique solutions. SOHO-LASCO reported $\sim$ 0.8 CMEs per day during our epoch of observations (St. Cyr et al., 2000). Given their latitudinal distribution, our data-set would sample almost all of them and this could be one of the many causes of inconsistencies in the data-set.

8.3 Radial evolution of Solar Wind

The dense coverage of the equatorial Solar Wind achieved in our data-set makes it a useful data-base for studying the radial evolution of the Solar Wind properties. We have studied the radial evolution of the Solar Wind velocity in this work. Our work has revealed a trend for the average equatorial IPS velocities to decrease with heliocentric distance. As this trend is different from expectations, we have performed a careful analysis and are convinced that the observed decrease is not an artifact due to the presence of some biases in the data-set or analysis procedure. The IPS velocity measurements are heavily weighted in favour of structures which are associated with significant amounts of turbulence (and hence higher C_n^2), because of the *l.o.s.* weight function. The observed trend can, therefore, be explained by the presence of structures which have higher levels of turbulence associated with them and which decelerate as they propagate outwards. Coronograph observations of CMEs during our epoch of observations (St. Cyr et al., 2000) show that IPDs due to CMEs fulfil all these requirements and we believe that slowing down of IPDs is the cause for the observed deceleration seen in the equatorial Solar Wind. We feel that this effect has not been seen earlier because of the lack of a suitable data-set.

The weighting of IPS velocities by a function proportional to $(\delta n_e)^4$ would also explain why the average *in-situ* velocity measurements from spacecrafts, which are not biased in this manner, may not show such a trend.

8.4 Future prospects of IPS tomography

8.4.1 Need for better S/N observations

IPS tomography aims at providing a global model for the distribution of Solar Wind properties in the inner heliosphere using the observed IPS power spectra as the constraints. For a good reconstruction it is necessary that the primary observable which is used for the tomographic reconstruction has enough information about the distribution of the Solar Wind which tomography can try to unravel. During the course of this analysis, we realised that the uniform Solar Wind models provide an adequate model for many of the observed power spectra primarily because most often the sensitivity and the reliability of the observations are not sufficient to discern the deviations from the uniform Solar Wind models.

Though the mean and the median χ^2 for the best fit uniform Solar Wind model to the observed power spectra are significantly less than unity (Section 5.5 and Figure 5.3), their distribution shows a systematic increase in χ^2 as the S/N of the observed power spectra increases. The χ^2 being a measure of the *significance* of the deviations of the model from the data, this trend implies that as the S/N of the power spectra improves, the significance of the deviations of the uniform Solar Wind model from the observed spectra increases.

Therefore, in order to make measurements which are sensitive to the structure in the Solar Wind, the S/N on the measurements of power spectra needs to be improved. This can be achieved by a variety of means - observing for longer durations, increasing the collecting area and the bandwidth of observations. The present IPS data acquisition system at the Ooty Radio Telescope uses only 4 MHz of the total 12 MHz of the signal bandwidth available, so an improvement of $\sqrt{3}$ in S/N, while maintaining the same observing duration, is achievable with a reasonable effort.

8.4.2 Tomography as a routine investigation tool

A fair amount of experience and insight was gained during this exercise about tomographic reconstruction using IPS data. We feel that though success in this exercise offers lucrative results, rigorous tomography of the type we have attempted, is not viable as a routine investigation tool. The assumption of little or no time evolution during the course of the observations which is necessarily required by this exercise is likely to met, if at all, for only very brief periods close to the minima of the solar activity cycle. The observational effort required to obtain a data-set suited for a tomographic reconstruction is enormous and necessarily requires a dedicated good sensitivity telescope.

Given the fact that even in the quietest parts of the solar cycle CMEs launched at the rate of about one per day, the problem of tomographic inversion will not become any more amenable to a non-unique reconstruction even if higher S/N observations are available. This bottleneck can be overcome only by ensuring that the entire heliosphere is sampled adequately on time scales shorter time scales of its variations. This cannot be achieved while being confined to the single vantage point of the Earth. Space radio telescopes with large collecting areas spread, say, all along the Earth's orbit can reduce the time taken to sample the entire heliosphere substantially and enable reliable tomography.

In spite of the bleak prospects of the success of rigorous IPS tomography, the subject is sufficiently interesting and the information it can yield cannot be obtained by any other means. It can certainly be used for qualitative estimates of the approximate 3D structure of the Solar Wind in conjunction with information from a variety of other sources both close to the Sun and at 1 *AU* which can be used as additional constraints.

Till the time we reach a stage where it takes much shorter durations to cover the entire heliosphere, using the data from spacecrafts which can provide different perspectives of the heliosphere with sufficient S/N to be sensitive to the structure along the IPS *l.o.s.*s, this technique cannot be used as a routine means of investigation of the Solar Wind.

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