Chapter 8

Cosmic ray modulation along the Voyager 2 trajectory and the north-south heliospheric asymmetry

8.1 Introduction

In the previous chapter, time-dependencies in the parallel and perpendicular diffusion and drift coefficients were proposed which led to compatible computed cosmic ray intensities at Earth and along the Voyager 1 trajectory when compared to different spacecraft observations. This chapter investigates cosmic ray modulation along the Voyager 2 trajectory by again comparing model results to $E > 70$ MeV observations. It is shown that the computed cosmic ray intensities along the Voyager 2 trajectory are not compatible to the observations when the same modulation parameters, as used along the Voyager 1 trajectory, are used. First, a parameter study is done by changing the magnitude and radial dependence of the different diffusion coefficients in order to improve compatibility. Thereafter the TS and heliopause positions are varied in the model and the effects on cosmic ray intensities along the Voyager 2 trajectory are shown. It is shown that this investigation confirms a geometrical asymmetry of the heliosphere from cosmic ray perspective (*Krymsky et al.*, 2009; *Manuel et al.*, 2011a; *Ngobeni and Potgieter*, 2011). Such an asymmetry was already proposed by MHD models (*Opher et al.*, 2006, 2009a,b; *Pogorelov et al.*, 2008b, 2009a,b).

8.2 Evidence of a heliospheric asymmetry based on observations and numerical models

Observations from Ulysses, the Voyagers and IBEX spacecraft and various MHD and other numerical models suggest a geometrical asymmetry of the heliosphere and structures inside. A brief overview of observations and numerical modelling studies which suggest an asymmetry is given. Note that this work only deals with the north-south asymmetry in the heliosphere, the asymmetry in the nose-tail and east-west of the heliosphere is not discussed.

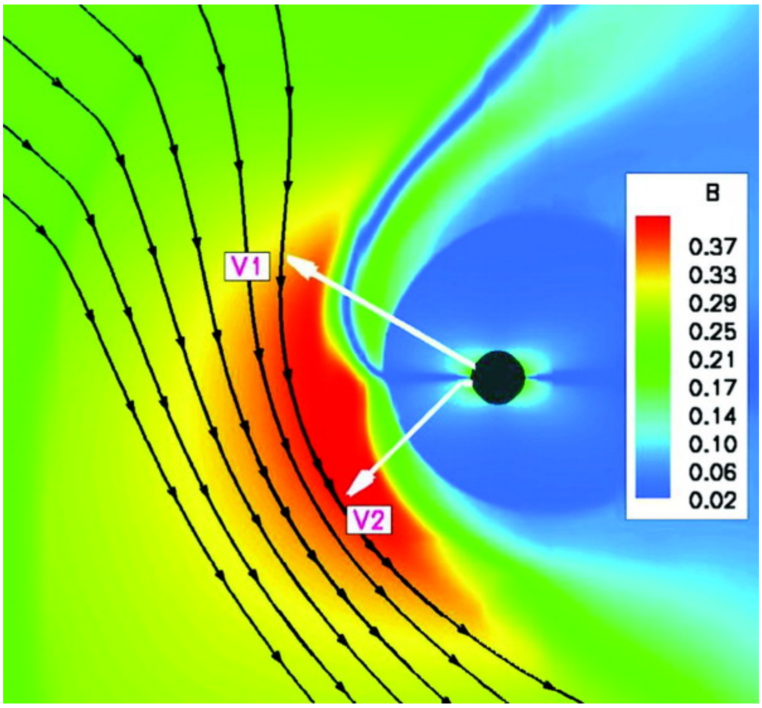

Figure 8.1: The meridional cut of the heliosphere showing the contours of the magnetic field magnitude. The black lines represent the ISMF and the white arrows the trajectories of Voyager 1 (V1) and Voyager 2 (V2) respectively. The HCS (dark blue) is deflected northward in the heliosheath. From *Opher et al.* (2006).

The first observational evidence of a north-south asymmetry in the heliospheric geometry and structures inside was inferred from Ulysses cosmic ray observations (*Smith et al.*, 2000). Ulysses was the first spacecraft to traverse towards the Sun's polar regions (see Chapter 2, Section 2.12.2 for an overview on Ulysses spacecraft). The measurements of galactic and anomalous cosmic rays on-board Ulysses revealed an asymmetry in the observed intensities with higher intensities in the northern heliospheric hemisphere (*Heber et al.*, 1996). From Wind and Ulysses spacecraft observations *Smith et al.* (2000) suggested the existence of a HCS which is displaced southward by $\sim 10^o$ during the declining phase of solar cycle 22. This proposed asymmetry helped to explain the north-south asymmetry of cosmic ray intensities measured by Ulysses. Later, *Erdos and Balogh* (2010) suggested a smaller asymmetry due to the displacement of HCS towards south ($\sim 2^o - 3^o$) during solar cycles 22 and 23. These authors also found a slightly stronger magnetic field in observations close to the south pole compared to the north pole. Also *Krymsky et al.* (2009) found a north-south asymmetry of the heliosphere in cosmic ray observations and suggested that HCS is shifted southwards by $\sim 7^o$.

Voyager 1 and Voyager 2 are twin spacecraft probing the northern and southern heliospheric hemispheres respectively. The trajectories of both the spacecraft are shown in Figure 2.29. See Chapter 2, Section 2.12.3 for an overview on both the spacecraft and on-board scientific investigations. A foreshock, ~85 AU and ~75 AU along the Voyager 1 and 2 respectively and a TS, ~94 AU and ~84 AU along the Voyager 1 and 2 respectively were measured. The shock is

∼10 AU closer to the Sun along the Voyager 2 trajectory compared to Voyager 1, indicating an asymmetry in the shock position (*Decker et al.*, 2005; *Stone et al.*, 2008) and/or a moving shock as a function of solar activity. The studies by e.g. *Snyman* (2007) and *Webber and Intriligator* (2011) indicated an asymmetric time-dependent TS along both Voyager trajectories.

Also numerical simulations done by *Opher et al.* (2006, 2009a,b) and *Pogorelov et al.* (2008b, 2009a,b) using MHD models also suggest an asymmetry between the two hemispheres due to an external pressure resulting from the interstellar magnetic field (ISMF). If the angle between the ISMF and interstellar velocity is non zero, it should break the axial symmetry of the heliosphere which traverses through the interstellar medium. This causes a distortion of the heliopause and the TS. These authors found that apart from a large nose-tail asymmetry, an asymmetry in both the north-south and east-west directions exists. Note that asymmetries in the internal pressure and/or high speed streams can also possibly be responsible for such an asymmetry.

Figure 8.1 shows the modelling result taken from *Opher et al.* (2006) which illustrates the meridional cut of the heliosphere with the contours that of the magnetic field magnitude. The black lines represent the ISMF and the white arrows the trajectories of Voyager 1 (V1) and Voyager 2 (V2) respectively. The HCS (dark blue) is seen deflected northward in the heliosheath. Due to the external pressure resulting from the ISMF, the heliosphere is distorted with the northern hemisphere bulged compared to the southern hemisphere. This simulation predicted a TS position ∼10 AU closer to the Sun along the Voyager 2 compared to Voyager 1, which was later confirmed by the Voyager 2 observations.

Pogorelov et al. (2008b, 2009a,b) shown that if ISMF strength is greater than 4 μG, it results in a ∼10 AU asymmetry of the TS as observed along the Voyager 1 and 2. Recently IBEX observations (*McComas et al.*, 2012) showed that the ISMF around the heliopause causes compression of the heliopause and the TS on the southern side of the heliosphere.

From a cosmic ray perspective, *Manuel et al.* (2011a) found that in the outer heliosphere, the Voyager 1 and 2 observations cannot be fitted with an identical set of transport parameters along both trajectories, suggesting a possible asymmetric heliosphere or a symmetric heliosphere but with different diffusion parameters in the northern and southern hemispheres respectively. Also work done by *Ngobeni and Potgieter* (2011, 2012) supports a north-south asymmetry in the heliosphere from the modulation of galactic cosmic ray carbon. In this chapter it will be shown that such an asymmetry is indeed needed to compute realistic cosmic ray modulation along the Voyager 1 and 2 trajectories.

8.3 Cosmic ray modulation along the Voyager 1 and 2 trajectories

As mentioned above, cosmic ray observations can provide insight into the structure of the heliosphere. Figure 8.2 shows the $E > 70$ MeV proton observations from Voyager 1 (circle

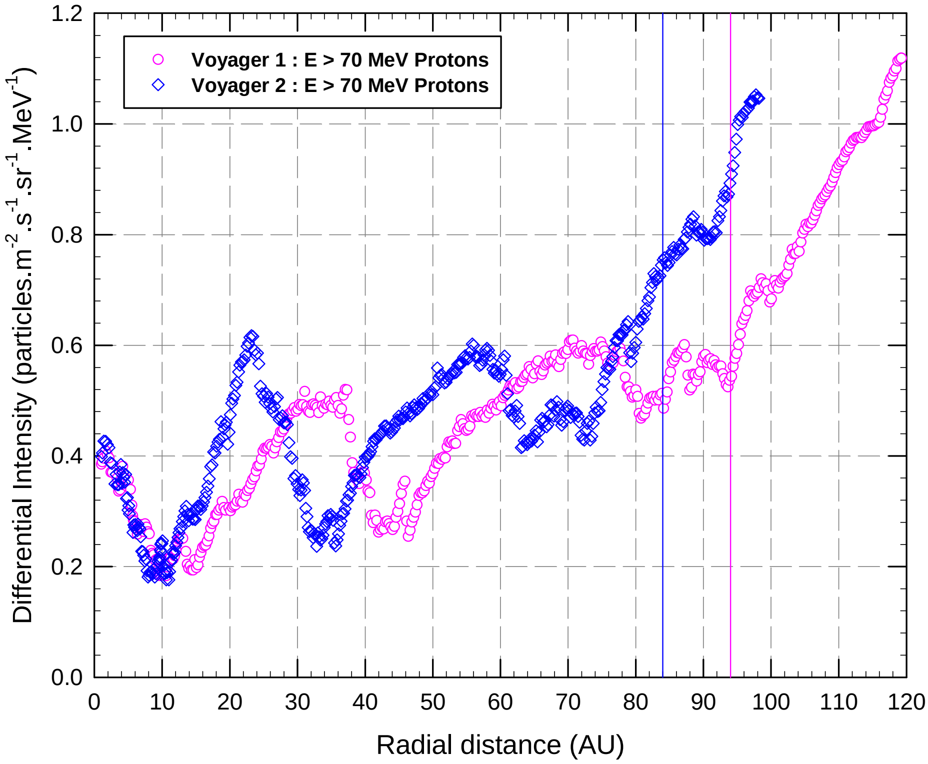

Figure 8.2: The $E > 70$ MeV proton observations from Voyager 1 (circle symbols) and Voyager 2 (diamond symbols) as a function of radial distance from the Sun (from http://voyager.gsfc.nasa.gov). The vertical pink and blue lines represent the TS position along the Voyager 1 and Voyager 2, respectively.

symbols), already shown in previous chapters, and Voyager 2 (diamond symbols) as a function of radial distance from the Sun (from http://voyager.gsfc.nasa.gov). As of January 2012, Voyager 1 is at ∼119 AU and Voyager 2 is at ∼97 AU from the Sun, i.e. Voyager 1 is ∼ 22 AU ahead of Voyager 2. Note that Voyager 1 passed the TS at 94 AU and Voyager 2 at 84 AU, as shown in the figure by vertical pink and blue lines respectively. Shown in Figure 8.2 is that Voyager 2 at ∼97 AU already measured intensities at the level which Voyager 1 measured at ∼116 AU, indicating that if the HPS is the same in both hemispheres, the heliosphere should be asymmetrical, e.g. smaller boundary along the Voyager 2 trajectory. The signature of such an asymmetry in cosmic ray observations are investigated next. See also *Ngobeni and Potgieter* (2011).

In the previous chapter, cosmic ray modulation at Earth and along the Voyager 1 was investigated. The computed results which were compatible to the observations at Earth and along the Voyager 1 trajectory for a heliopause distance of 119 AU, TS position of 90 AU (average position of the TS), $C_1 = 4.0$, $C_2 = 0.7$, $a = 0.022$, $b = 0.01$ and $K_{A0} = 0.8$. Figure 8.3 shows the computed cosmic ray intensities at Earth and along the Voyager 1 and 2 trajectories using the above mentioned parameters. However, when these parameters are assumed for calculations

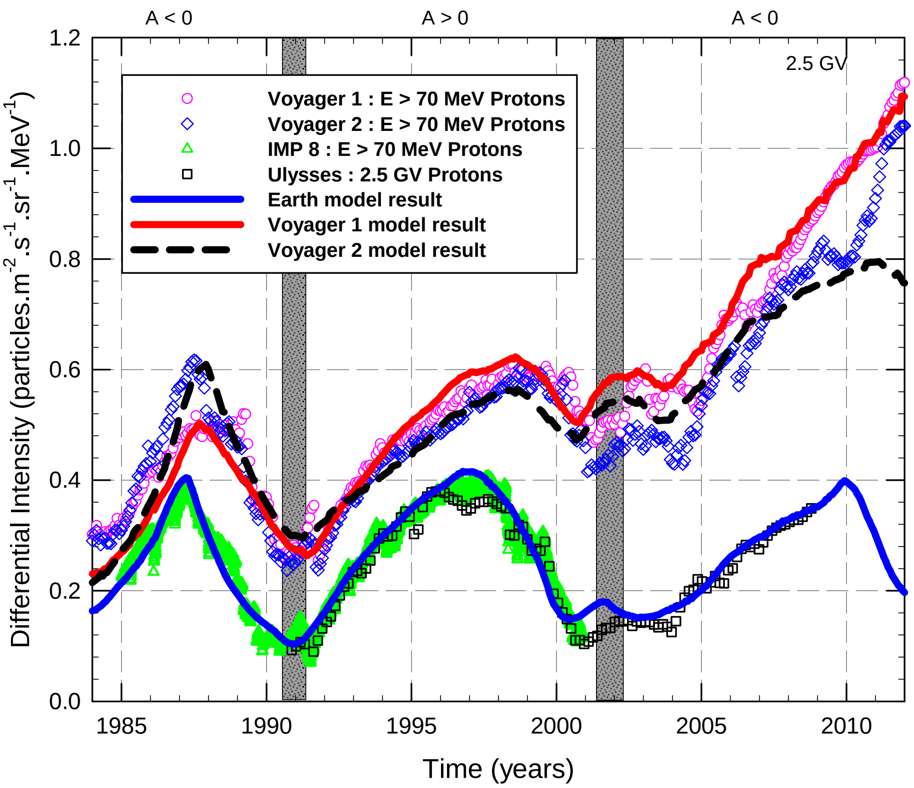

Figure 8.3: Computed 2.5 GV cosmic ray proton intensities at Earth and along the Voyager 1 and 2 trajectories since 1984 are shown as a function of time. Also shown are the $E > 70$ MeV proton observations from Voyager 1 and 2 (from `http://voyager.gsfc.nasa.gov`) as symbols (circles and diamonds) and $E > 70$ MeV measurements at Earth from IMP 8 (from `http://astro.nmsu.edu`) (triangles) and $\sim$ 2.5 GV proton observations (squares) from Ulysses (*Heber et al.*, 2009). The shaded areas represent the periods where there were not a well defined HMF polarity.

along the Voyager 2 trajectory, the computed cosmic ray intensities are globally compatible to the observations only until ~2010, afterwards the model computes intensities much lower than the observations. A solar cycle is visible in the computed cosmic ray intensities due to the possible large modulation volume ahead of Voyager 2 up to the heliopause. In contrast, the observations show increasing cosmic ray intensities along the Voyager 2 after ~2010, without showing a prominent solar cycle dependent effect.

8.4 Modelling results along the Voyager 2 trajectory

From Figure 8.3, it follows that when the same modulation parameters as used along the Voyager 1 are also used along the Voyager 2 trajectory, the computed cosmic ray intensities failed to reproduce the observations especially from ~2010 onwards. This can either suggest a symmetrical heliosphere but with different modulation parameters in different hemispheres (e.g. *Ngobeni and Potgieter*, 2011) or an asymmetrical heliosphere and different modulation parameters along both Voyager trajectories. These scenarios are now investigated by first consider-

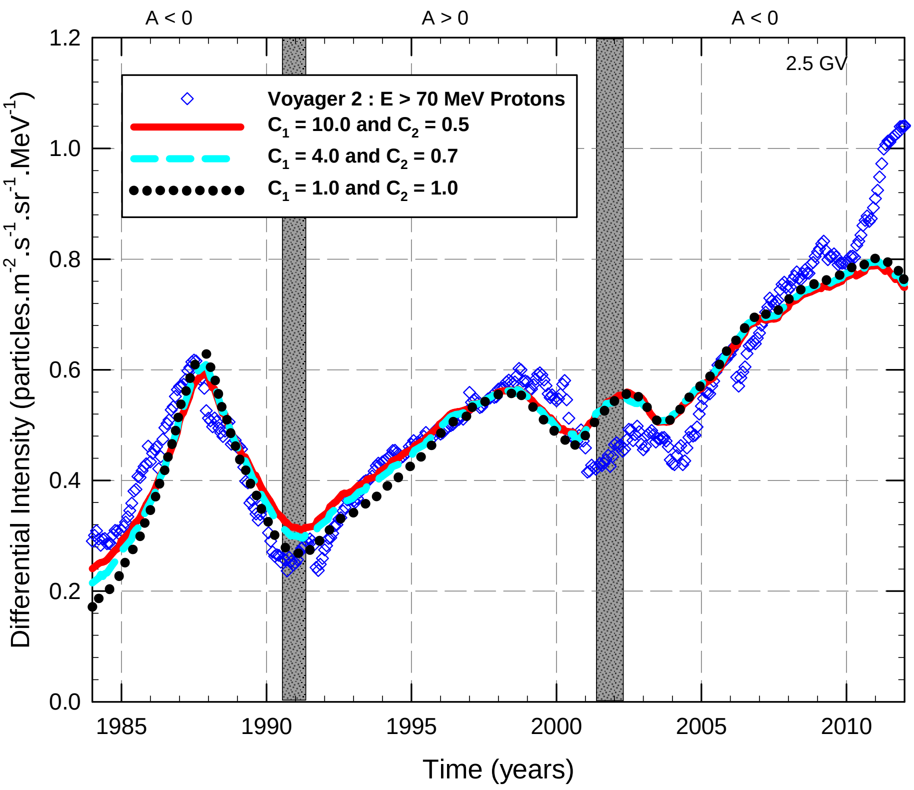

Figure 8.4: Computed 2.5 GV cosmic ray proton intensities along the Voyager 2 trajectory since 1984 are shown for three different C_1 and C_2 scenarios as a function of time. Also shown are the $E > 70$ MeV proton observations from Voyager 2 (from http://voyager.gsfc.nasa.gov) as symbols (diamond). The shaded areas represent the periods where there were not a well defined HMF polarity.

ing a symmetrical heliosphere but with different modulation parameters in the northern and southern heliospheric hemispheres respectively. This is achieved by changing C_1, a constant which determine the absolute value of the mean free paths, C_2, a constant determining the radial dependence and a, the ratio of perpendicular diffusion coefficient in radial direction to the parallel diffusion coefficient and then compare these computed cosmic ray intensities with the Voyager 2 observations. Later, an asymmetric heliosphere is assumed by first changing the TS position and then the heliopause position in the southern hemisphere only. Note that the HPS assumed here are the same as assumed in the previous chapter. In the next chapter this effect is investigated in more detail.

8.4.1 Effect of different C_1 and C_2 values

The effect of different C_1 and C_2 values, as given in Equations 6.1 and 6.2, on cosmic ray intensities is shown in Figure 8.4. The C_1 value determines the magnitude of the transport coefficients at Earth and C_2 the radial dependence. The figure shows three different scenarios with different C_1 and C_2 values. From the figure it follows that all the three different combinations of C_1 and C_2 computed nearly the same cosmic ray intensities. Note that compatibility with

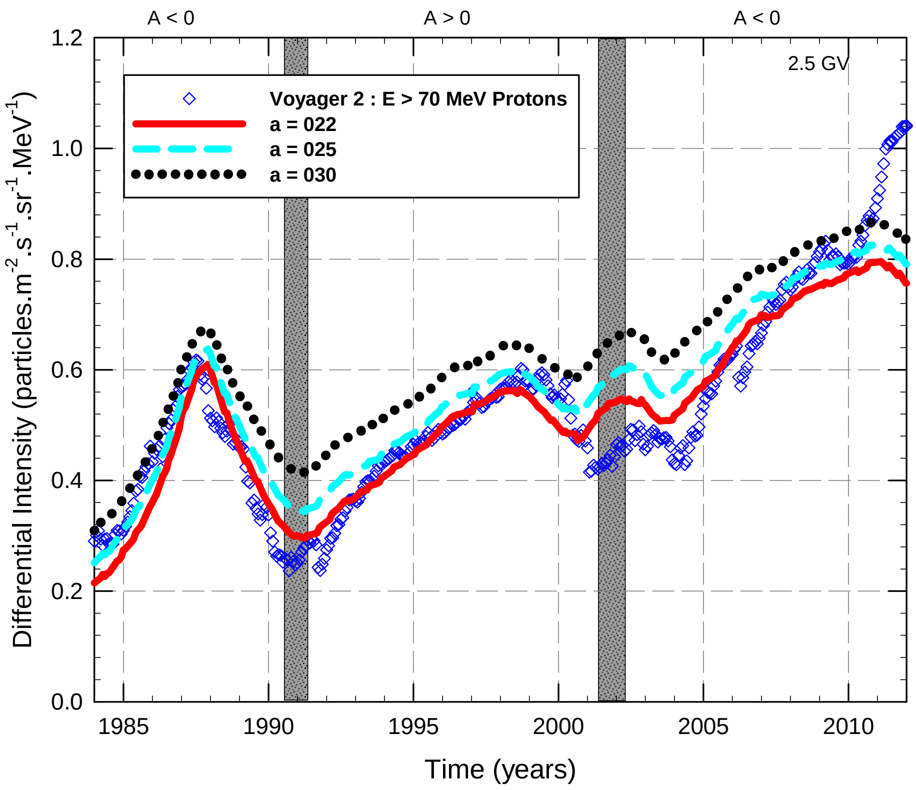

Figure 8.5: Similar to Figure 8.4 except that here modelling results along the Voyager 2 trajectory are shown for different a values.

observations up to ∼2010 is computed but the changes in the C_1 and C_2 values, as shown in Figure 8.4, fail to reproduce compatibility with observations along the Voyager 2 from ∼2010 onwards. For this period the computed intensities are still decreasing according to the solar cycle while the observations show a steady increase.

8.4.2 Effect of different a values

The effect of the ratio of the perpendicular diffusion coefficient in the radial direction to the parallel diffusion coefficient, a, as given in Equation 6.6, on cosmic ray intensities along the Voyager 2 trajectory is shown in Figure 8.5. The figure shows three different scenarios with a values 0.022, 0.025 and 0.030 respectively. From the figure it follows that a smaller a value results in compatible modelling results when compared to the observations during solar maximum periods but during solar minimum periods an increased a value better suits the observations. However, from the computed results it can be seen that after increasing the a value, even to 0.030, the model still fails to reproduce the steep increase in cosmic ray intensities as observed along the Voyager 2 after ∼2010. The computations produce intensities decreasing after ∼2010, again showing a clear solar cycle dependence similar to what is shown in Figure 8.4. This illustrates that any change in the diffusion coefficients is not sufficient enough to

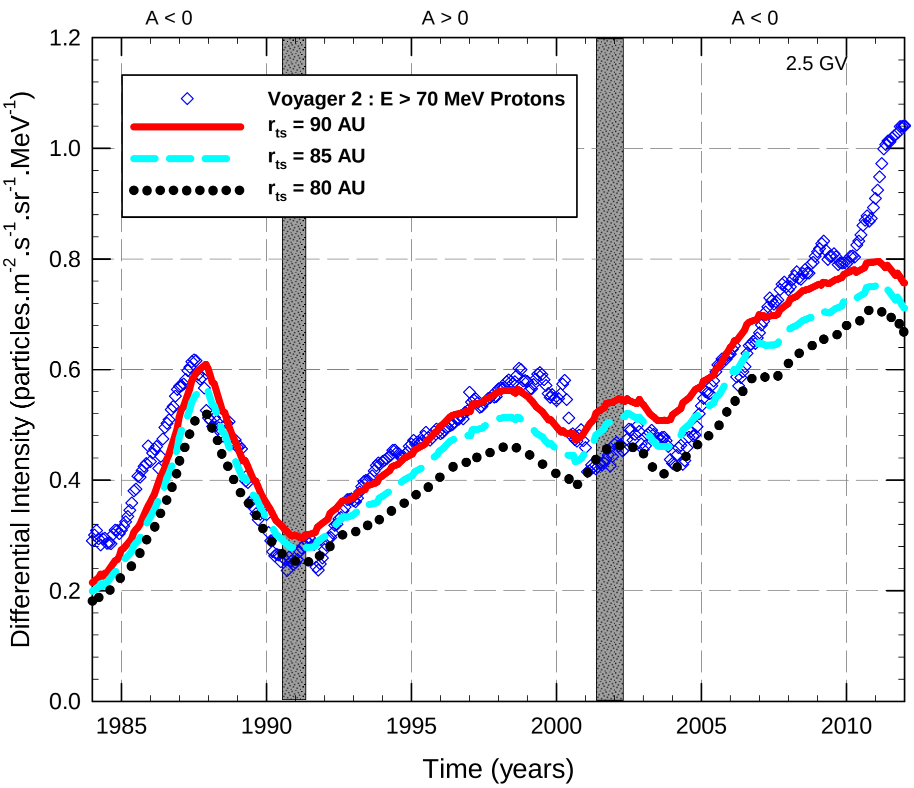

Figure 8.6: Similar to Figure 8.4 except that here model results along the Voyager 2 trajectory are shown for different TS, r_{ts}, positions.

reproduce the observations when a symmetric heliosphere is assumed.

8.4.3 Effect of different termination shock positions

The effect of different TS positions on the 2.5 GV cosmic ray intensities along the Voyager 2 trajectory is shown in Figure 8.6. Three different scenarios are assumed. Considering the observation when Voyager 2 crossed the TS at ∼84 AU (*Richardson et al.*, 2008; *Stone et al.*, 2008) a position of 85 AU from the Sun is assumed. A smaller TS position, 80 AU, and a larger one at 90 AU, are also assumed. These values are within the range of numerical simulations done by *Snyman* (2007) and *Webber and Intriligator* (2011). Note that the heliospheric boundary is kept at 119 AU. From the figure it follows that when the heliosheath thickness is increased, by decreasing the TS position, r_{ts}, the computed intensities are lower than the observations in the entire heliosphere, especially during solar minimum periods. This is because of the smaller diffusion coefficients in the inner heliosheath. Note that for these calculations, the shock position is stationary and the effects of different shock positions are more pronounced than the case of a dynamic shock. In Chapter 10 a dynamic (see also *Snyman*, 2007; *Webber and Intriligator*, 2011) TS is implemented in the model.

However, as shown in Figure 8.6, all r_{ts} scenarios still give computed intensities which de-

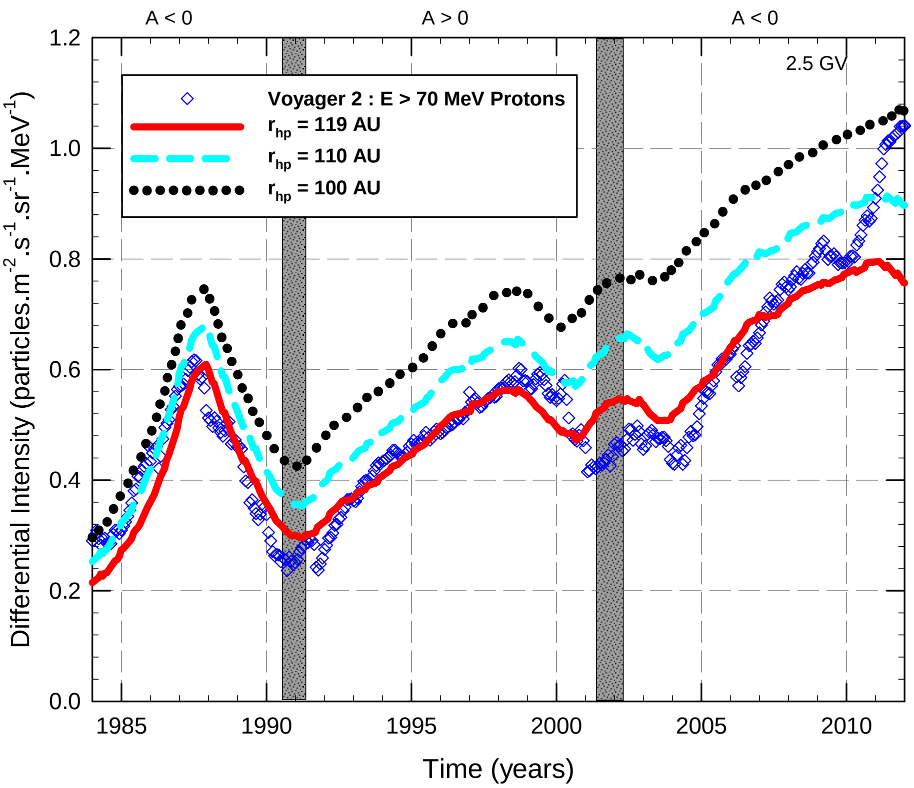

Figure 8.7: Similar to Figure 8.4 except that here modelling results along the Voyager 2 trajectory are shown for different heiopause, r_{hp}, radii.

crease after ∼2010. The computed intensity profiles show a clear solar cycle dependent effect as opposed to the observations which show a steady increase in cosmic ray intensities.

8.4.4 Effect of different heliopause positions

The heliosheath is a prominent feature that contributes to the modulation of cosmic rays in the heliosphere (*Webber and Lockwood*, 2001; *Langner et al.*, 2003; *Stone et al.*, 2008). In Figure 8.7, the TS position is assumed at 90 AU and the heliopause distance is moved from 119 AU to 110 AU and then to 100 AU respectively. The figure shows that when the thickness of the heliosheath is decreased from 29 AU ($r_{hp} = 119$) to 10 AU ($r_{hp} = 100$), the solar cycle effect on the computed cosmic ray intensities (as seen for a $r_{hp} = 119$ AU) starts to disappear in the outer heliosphere after ∼2010 (as seen for $r_{hp} = 110$ AU). For the $r_{hp} = 100$ AU scenario, the computed results in the outer heliosphere with nearly no visible solar cycle effects due to thinner inner heliosheath. This suggests that for the parameters assumed in the model, in order to fit the observations along the Voyager 2 trajectory, the heliosheath thickness must be reduced from 29 AU needed to fit Voyager 1 observations to an optimal value which will remove the solar cycle related effects in the computed intensities along the Voyager 2 after ∼2010 (see *Manuel et al.*, 2011a).

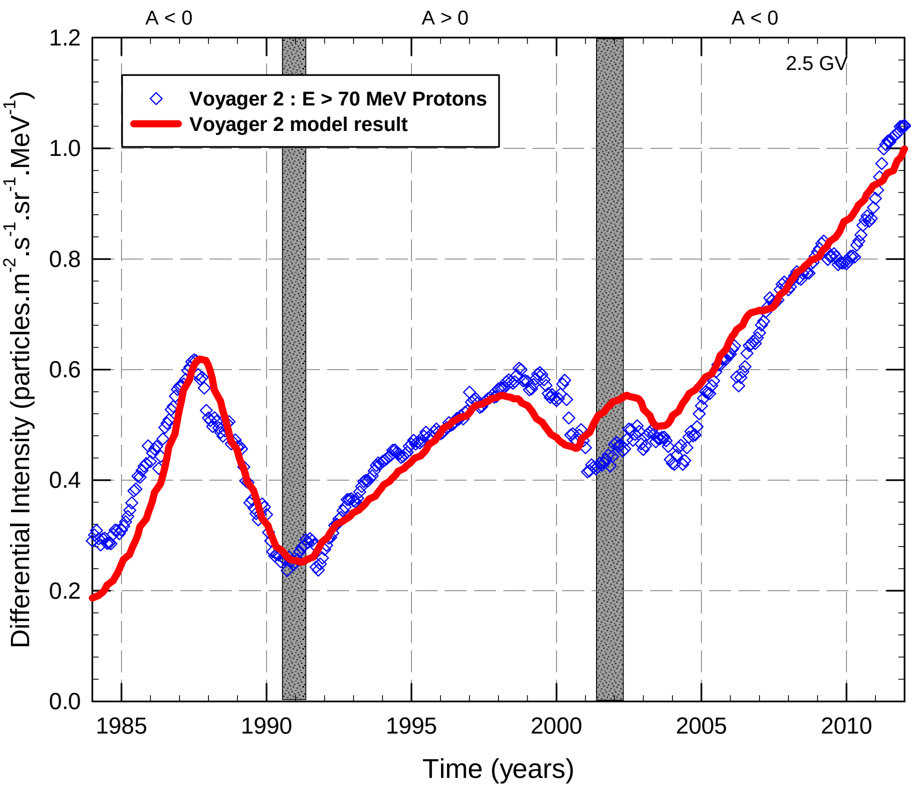

Figure 8.8: Similar to Figure 8.4 except that here an optimal modelling result along the Voyager 2 trajectory is shown.

8.5 An optimal model result along the Voyager 2 trajectory

Calculations of cosmic ray modulation along the Voyager 2 trajectory are now optimised by changing the heliopause position from 119 AU to 100 AU, the TS from 90 AU to 80 AU, the a value from 0.022 to 0.017 and K_{A0} from 0.8 to 0.9 compared to the case for Voyager 1. This optimal result is shown in Figure 8.8 and compared to observations. Here the computed result is compatible to the Voyager 2 observations also after ∼2010. This result could be one of the possible scenarios for the assumed parameter sets to compute cosmic ray intensities along the Voyager 2 trajectory when the same HPS is assumed as along the Voyager 1. Due to the limitations of this model with no modulation beyond the heliopause, the HPS could be different along the Voyager 2 and this aspect will be discussed in next chapter. However, Figure 8.8 suggests that the model, with the assumed transport parameters, predicts an asymmetrical heliosphere (modulation volume) and also slightly different parameters in the different hemispheres (*Ngobeni and Potgieter*, 2011; *Scherer et al.*, 2011).

The computed cosmic ray distribution in the heliosphere during different solar activity and magnetic polarity cycles are now shown in Figures 8.9, 8.10 and 8.11. Figure 8.9 shows the 2.5 GV proton distribution during the 1997 solar minimum with an $A > 0$ polarity cycle. The

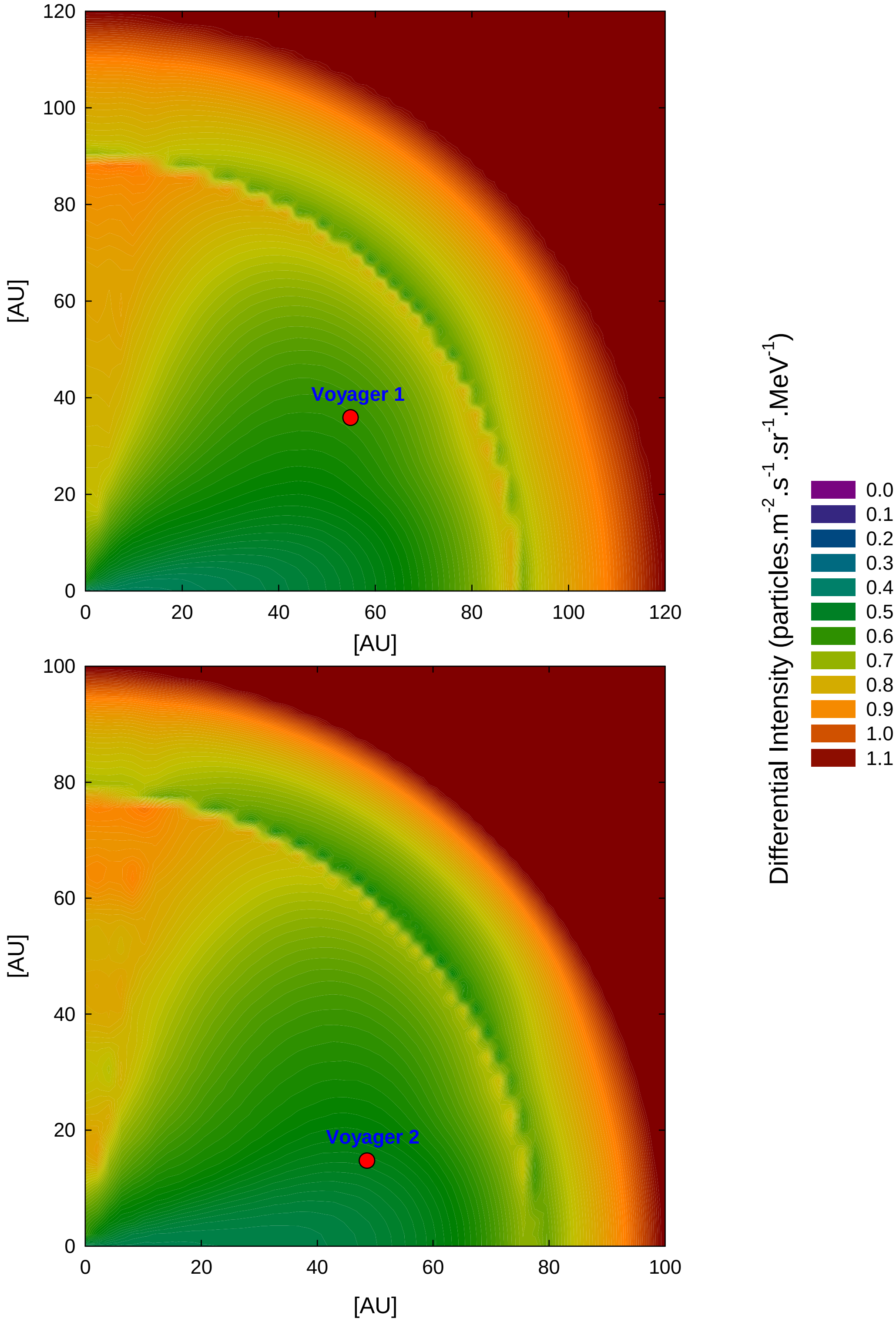

Figure 8.9: Top panel shows the contour plot showing the distribution of 2.5 GV protons in the heliosphere from the heliospheric north pole to the equatorial plane (nose) during the $A > 0$ magnetic polarity cycle of the 1997 solar minimum. Bottom panel shows the same but from heliospheric south to equatorial plane. Also both panel shows the position of Voyager 1 and 2 spacecraft during this period. The legend on the right side shows the differential intensity.

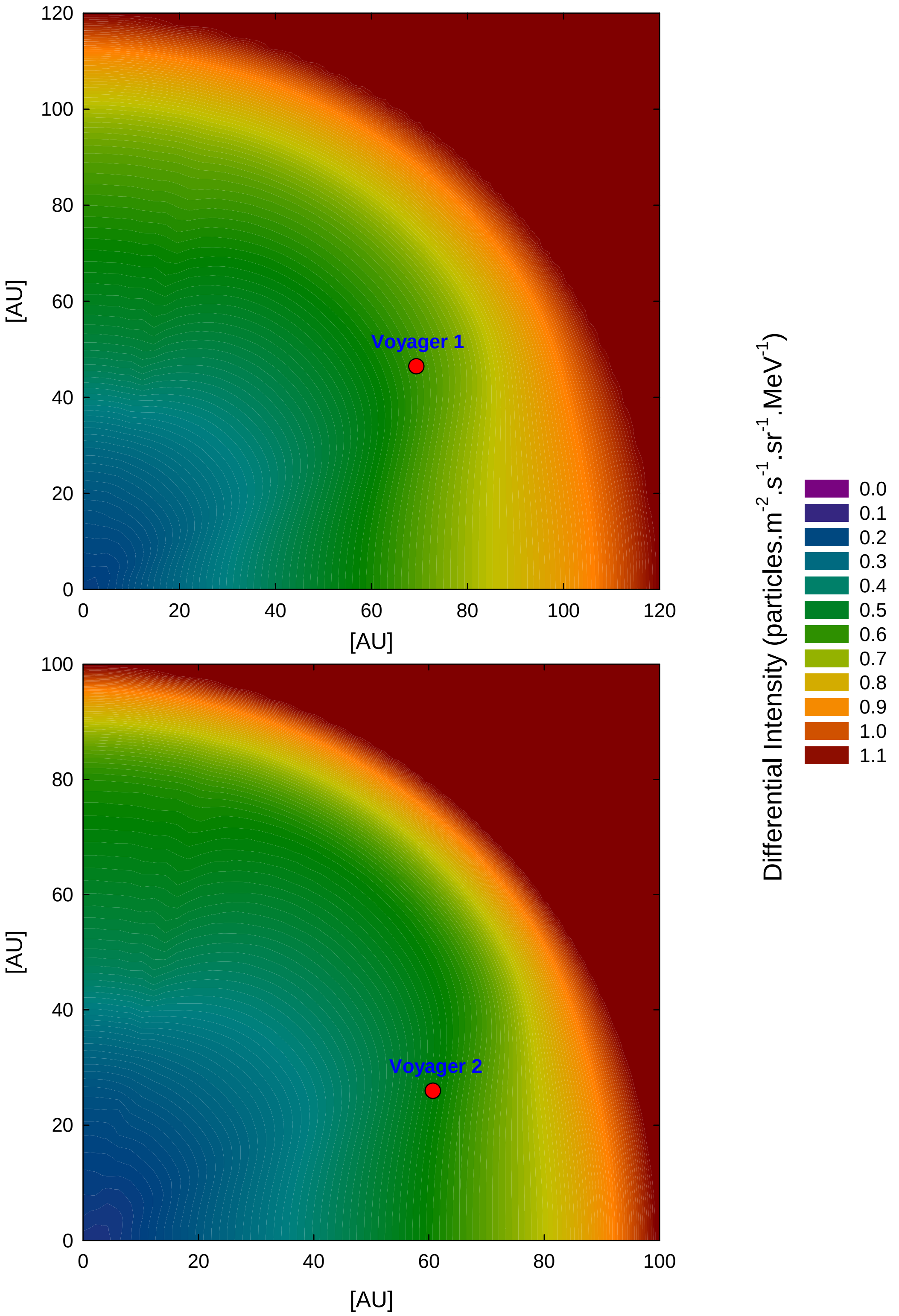

Figure 8.10: Similar to Figure 8.9 except that here contour plots show the distribution of 2.5 GV protons in the heliosphere during the 2002 solar maximum.

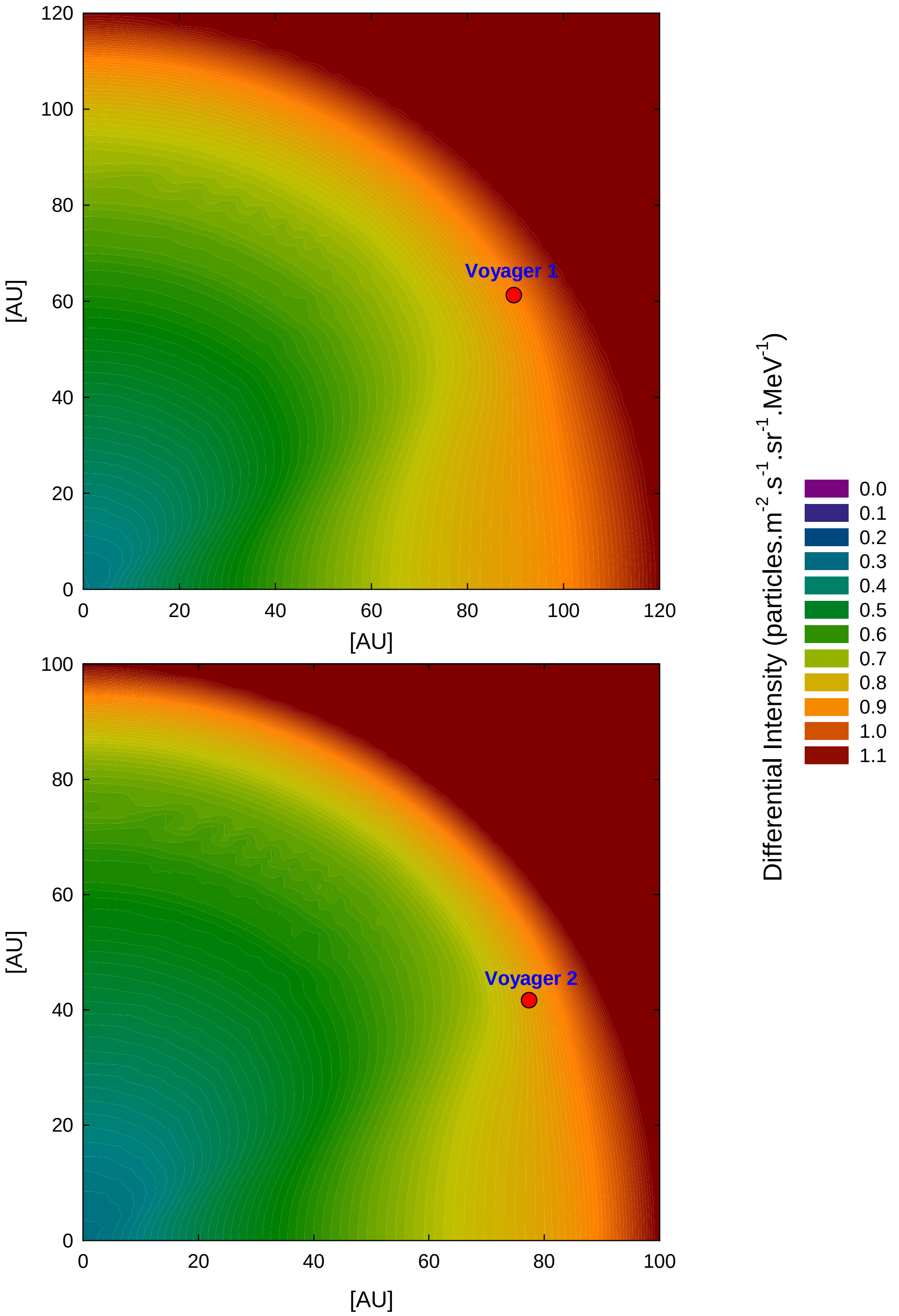

Figure 8.11: Similar to Figure 8.9 except that here contour plots show the distribution of 2.5 GV protons in the heliosphere during the $A < 0$ magnetic polarity cycle of the 2009 solar minimum.

top panel of the figure shows the meridional proton distribution in the heliospheric quadrant containing the north pole and the equatorial nose region. The bottom panel shows the same but for the heliospheric quadrant containing the south pole and the equatorial nose region. Also both panels show the positions of Voyager 1 and 2 at that specific period. From the figure it follows that during the $A > 0$ polarity cycle, protons enter the heliosphere mainly through both the polar regions and exit along the HCS. Higher cosmic ray intensities are observed during this cycle in the polar regions compared to the equatorial plane as shown in the figure. Also the TS position is visible during this cycle due to a decrease in the diffusion and drift coefficients beyond the shock. Note that the heliopause assumed along the Voyager 1 is at 119 AU but along the Voyager 2 is at 100 AU.

Figure 8.10 is similar to Figure 8.9 but for the solar maximum period of 2002. The figure shows that during this period there is no clear magnetic polarity and therefore protons diffuse in along all the possible directions. An almost even distribution of cosmic rays are computed along the different heliographic latitudes from the equatorial plane to the poles during this period. Again note the positions of Voyager 1 and 2 during this period.

Figure 8.11 also is similar to Figure 8.9 but for the solar minimum period of 2009 for an $A < 0$ polarity cycle. During an $A < 0$ polarity cycle the protons drift in along HCS and exit through the polar regions of the heliosphere. The figure shows that during this period the protons drift in mainly through the equatorial regions and a high cosmic ray intensities are observed compared to the polar regions. The positions of both the Voyagers are shown, with Voyager 1 seen closer to the assumed heliopause position.

8.6 Summary and conclusions

In Chapters 6 to 7 cosmic ray modulation were investigated along the Voyager 1 trajectory and at Earth. In this chapter the focus is shifted to investigating cosmic ray intensities along the Voyager 2 trajectory by comparing the computed results with the Voyager 2 observations. The study revealed that when the same modulation parameters were assumed, which resulted in compatible intensities along the Voyager 1, the model failed to reproduce the observations along the Voyager 2 trajectory. This suggested that different transport parameters must be assumed in the different heliospheric hemispheres and/or an asymmetry in heliospheric geometry. This was investigated and it was found that any changes in diffusion parameters alone could not reproduce the cosmic ray observations along the Voyager 2 and that changes to the heliospheric geometry were required.

The effect of changes in the TS position alone on cosmic ray intensities was first investigated by keeping the same heliopause position and varying the shock position. It was found that if the heliosheath thickness was made smaller by changing the shock and keeping the boundary the same, the model still computed a solar cycle dependence with decreasing intensities after ~2010 along the Voyager 2 trajectory whereas the observations show a gradual increase in intensities. This is because Voyager 2 at $\sim$91 AU in 2010 is still relatively far from the boundary with enough modulation volume between it and the boundary to compute solar cycle effects. In the next step, the heliosheath thickness was reduced by changing the heliopause position from 119 AU for Voyager 1 to 100 AU for Voyager 2. An optimal modelling result compatible to the cosmic ray observations along the Voyager 2 was computed. The computed cosmic ray intensities along both Voyagers suggest that our heliosphere is an asymmetric heliosphere. However, this scenario could change if a different HPS is assumed along the Voyager 2, which is discussed in next chapter.