Chapter 9

Prediction of cosmic ray intensities along the Voyager 1 and 2 trajectories

9.1 Introduction

In the previous chapters, time-dependent cosmic ray modulation at Earth and along the Voyager 1 and Voyager 2 trajectories were investigated until 2012. In this chapter, possible future $E > 70$ MeV (∼2.5 GV) and 133-242 MeV (∼200 MeV) protons intensities are predicted along the Voyager 1 and 2 spacecraft trajectories for time periods > 2012. The 2.5 GV and 200 MeV cosmic ray proton intensities along the Voyager 1 is first modelled assuming a HPS as the intensity observed by Voyager 1 at ∼119 AU. This HPS is then used to model the cosmic ray intensities also along the Voyager 2 trajectory and the respective heliopause (modulation boundary) distance from the Sun along the Voyager 2 trajectory is interpreted from the model results. In this chapter, the model is also used to compute cosmic ray intensities along the Voyager 1 and Voyager 2 trajectories for different HPS scenarios and for different boundary distances.

By comparing the modelling results to Voyager 1 and Voyager 2 proton observations with $E > 70$ MeV, it is shown that the difference in radial distance to the modulation boundary between the two spacecraft results in different observed radial gradients on their way towards the boundary. This is because of solar cycle related changes in tilt angle, magnetic field magnitude and variance that are propagated outwards in the model. With a larger distance from the boundary for Voyager 2, compared to Voyager 1, solar cycle related variations in cosmic ray intensities may still be evident in future Voyager 2 observations. This is in contrast with Voyager 1 measurements where the model predicts a steady increase in intensities up to the modulation boundary. As shown, this is dependent on the assumption of the HPS and the boundary distance.

The model is also compared to a lower energy channel, 133-242 MeV proton observations onboard both Voyagers. This is to show that the conclusions which are made and based on the comparison of the model to $E > 70$ MeV proton observations are also valid for lower energies.

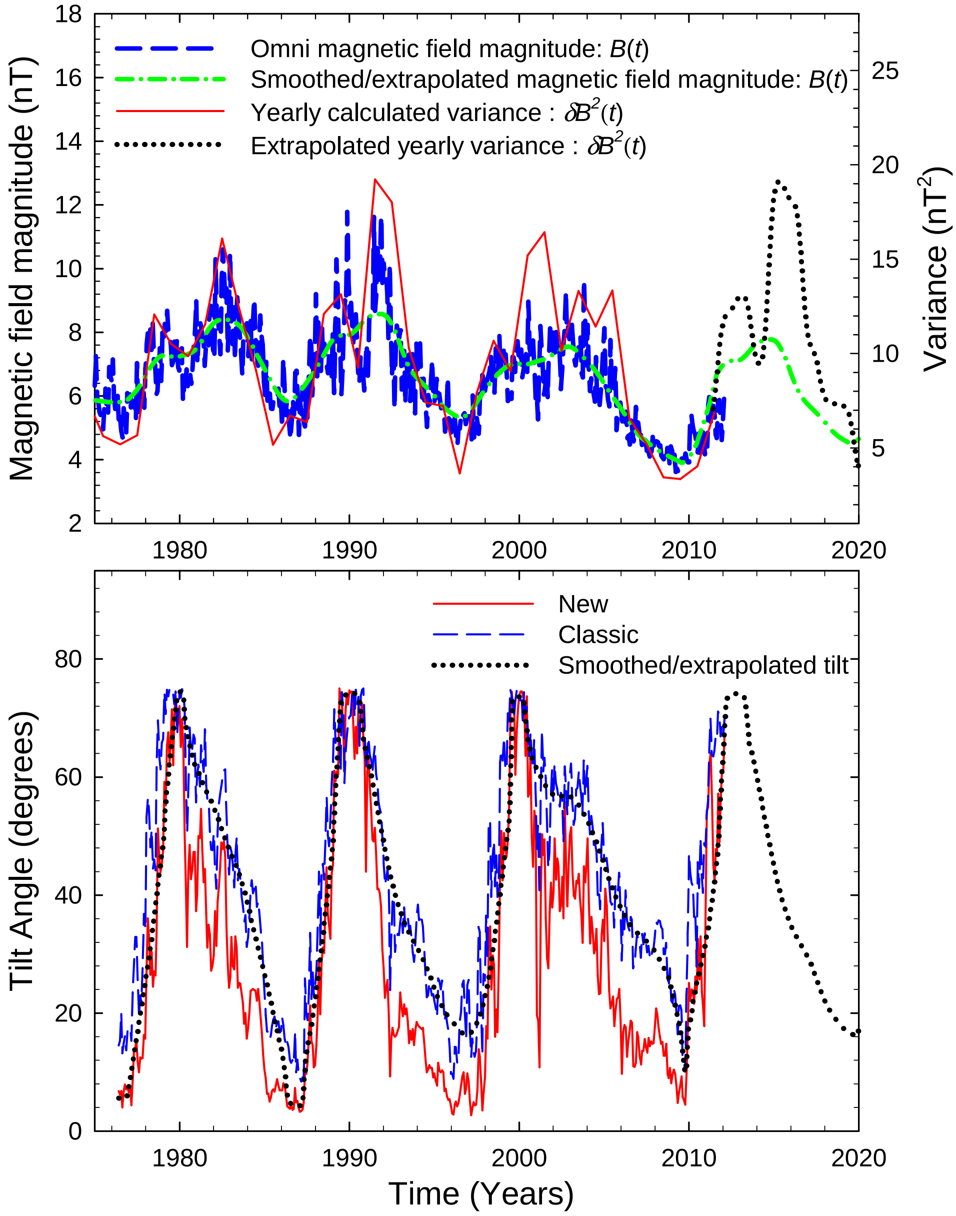

Figure 9.1: The top panel shows the observed HMF magnitude at Earth (from NSSDC COHOWeb: `http://nssdc.gfc.nasa.gov/cohoweb`), the calculated yearly statistical variance, the magnetic field magnitude and the variance values assumed from 2012 onwards for prediction purposes. The bottom panel shows the tilt angle as a function of time (see Wilcox Solar Observatory: `http://wso.stanford.edu`) based on two different tilt angle models using different boundary conditions, namely the "new" and the "classic" model (*Hoeksema*, 1992) and also the predicted tilt angle from 2012 onwards.

9.2 Input parameters

In order to predict future cosmic ray measurements along the trajectories of both Voyager spacecraft, time-dependent model input parameters need to be specified. This include the tilt angle of the HCS, the magnetic field magnitude and variance. For this purpose, a solar cycle, the same as that for the ∼1987 solar minimum onwards, is assumed for the period from 2012 onwards. The smoothed/extrapolated input parameters are shown in Figure 9.1. The top panel of the figure shows the observed OMNI magnetic field observations until 2012 (from NSSDC COHOWeb: http://nssdc.gfc.nasa.gov/cohoweb) represented by a blue dashed line. The total variance was calculated using the OMNI data as discussed in Chapter 6. The observed hourly averages of the total field magnitude were binned in 1 year intervals, and then the statistical variance in each interval was calculated until 2012 (*Strauss*, 2010). This is shown as the red solid line in the top panel of Figure 9.1. Also, the top panel shows the smoothed and extrapolated magnetic field magnitude and variance assumed from 2012 onwards as dashed-dotted green and dotted black lines respectively. To extrapolate the magnetic field magnitude B and the total variance δB^2 for the period from 2012 onwards a solar cycle the same as that for the ∼1987 solar minimum onwards, for both the parameters, is assumed. However, for the magnetic field, due to the unusual 2009 solar minimum conditions (*Heber et al.*, 2009; *McDonald et al.*, 2010; *Mewaldt et al.*, 2010), it is assumed that the field magnitude is 10% less than that of the 1986-1996 period.

The bottom panel of Figure 9.1 shows the computed tilt angle as a function of time (see Wilcox Solar Observatory: http://wso.stanford.edu) based on two different tilt angle models using different boundary conditions, namely the "new" and the "classic" model (*Hoeksema*, 1992) as red solid and blue dash lines respectively. For the predicted tilt angle from 2012 onwards a solar cycle the same as the ∼1987 solar minimum is assumed, which is shown in the bottom panel of Figure 9.1 as a black dotted line.

Figure 9.2 shows the time-dependent function $f_1(t)$ (black dotted line) in the drift coefficient, as given in Equation 6.11, which uses tilt angles as an input parameter. This function varies with solar activity from ∼0 during solar maximum to ∼0.9 for solar minimum. The figure also shows the time-dependence in the parallel and perpendicular diffusion coefficients produced by the functions $f_2'(t)$ in Equation 7.4 (solid red line) and $f_3'(t)$ in Equation 7.6 (dashed blue line) using the input parameters B and δB^2. These functions vary over solar cycle with $f_2'(t)$ resulting in an amplitude between solar minimum and solar maximum by a factor of ∼5 while $f_3'(t)$ only changes by a factor of ∼2 between solar minimum and maximum.

For this study, a HPS of protons (as shown in Figure 6.12) is constructed from the $E > 70$ MeV (∼2.5 GV) and 133-242 MeV (∼200 MeV) protons observations from Voyager 1 at ∼119 AU. The intensity values of these are specified at the heliopause as a HPS. Figure 9.3 shows the $E > 70$ MeV and 133-242 MeV proton observations from Voyager 1 (circle symbols) and Voyager 2 (diamond symbols) as a function of time (from http://voyager.gsfc.nasa.gov). The vertical dotted line represents the period where Voyager 1 is at a distance of ∼119 AU (the assumed boundary in the model along the Voyager 1 trajectory). Shown by horizontal dashed lines are the intensities for $E > 70$ MeV and 133-242 MeV protons at the assumed modulation boundary. Later, in order to illustrate the effects of a possible higher HPS on model results, this

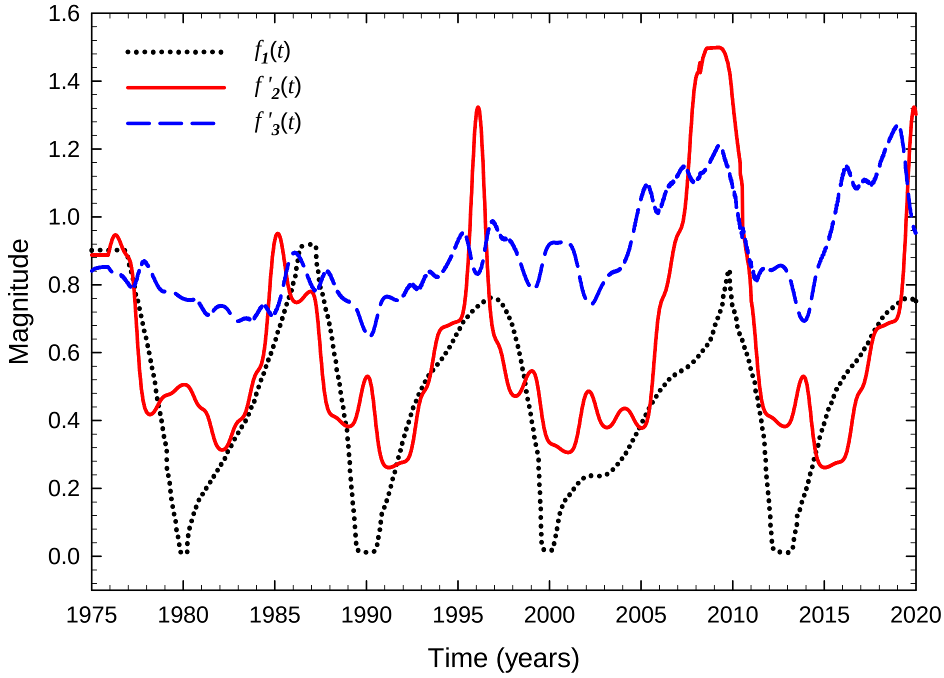

Figure 9.2: The time-dependent functions $f_1(t)$ in Equation 6.11 as dotted black line, $f_2'(t)$ in Equation 7.4 as solid red line and $f_3'(t)$ in Equation 7.6 as dashed blue line, until 2020.

assumed HPS is increased (at these energies) by 10% and then by 30% respectively.

9.3 Modelling results

Figure 9.4 shows the computed 2.5 GV intensities up to ~2020 along the Voyager 1 and Voyager 2 trajectories, as the red solid and black dashed lines respectively. Computations are compared to the $E > 70$ MeV proton observations from Voyager 1 and 2 shown as circle and diamond symbols respectively. The figure illustrates that in general the computed intensities over different solar cycles are compatible with what has been observed along the Voyager 1 trajectory until reaching the assumed modulation boundary, the heliopause. However, along the Voyager 2 trajectory the computed results compare well with the observations up to ~2010. After ~2010, the computed results deviate from the observations along the Voyager 2 when a symmetrical heliosphere (TS position, $r_{ts} = 90$ AU and heliopause position, $r_{hp} = 119$ AU) and the same transport parameters as along the Voyager 1 is assumed along the Voyager 2. See the previous chapter for model results with an asymmetrical heliosphere.

Also note that some differences are evident on a smaller time scale, especially when step-like decreases/increases are observed. Although step-like decreases/increases are computed, it is less pronounced than what is observed, especially towards solar maximum. As mentioned in the previous chapter, this is a clear indication that the model does require in addition some

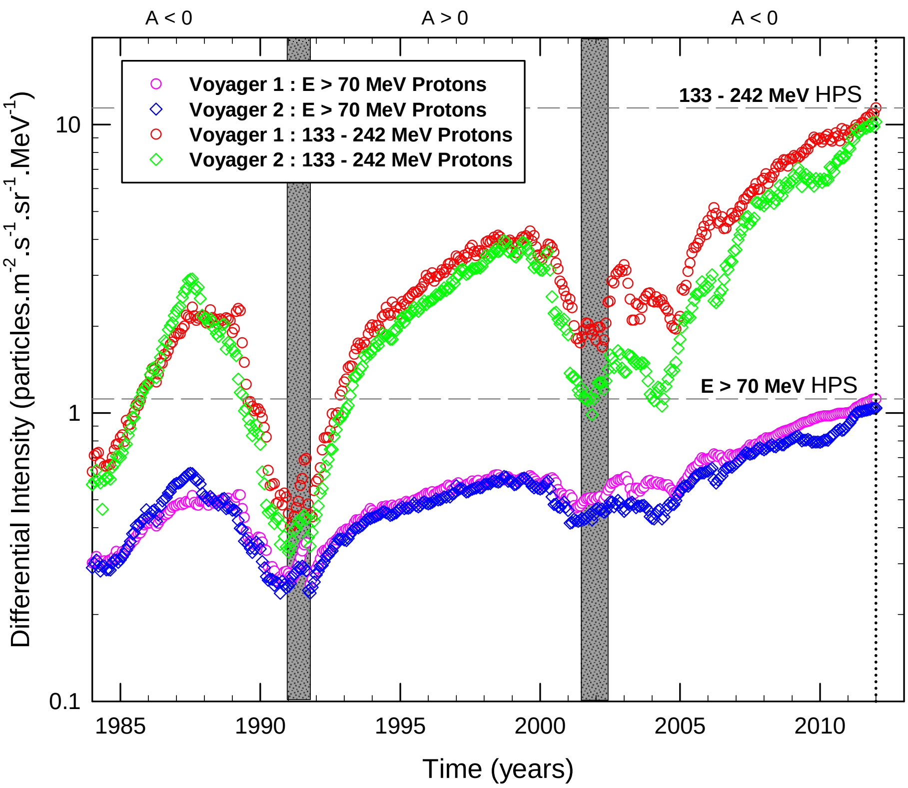

Figure 9.3: The $E > 70$ MeV and 133-242 MeV proton observations from Voyager 1 (circle symbols) and Voyager 2 (diamond symbols) as a function of time (from http://voyager.gsfc.nasa.gov). The vertical dotted line represents the period where Voyager 1 is at ~119 AU, the assumed modulation boundary in the model along the Voyager 1 trajectory. Shown by horizontal dashed lines are the assumed HPS values for $E > 70$ MeV and 133-242 MeV protons. The shaded areas represent the periods where there were not a well defined HMF polarity.

form of merging along the way into more pronounced barriers for these extreme modulation conditions (see also *Manuel et al.*, 2011c,d).

As discussed above, as both spacecraft move outward towards the modulation boundary the intensities show a gradual increase together with a decreasing modulation amplitude between solar minimum and solar maximum periods. Due to drifts, the measured intensities of Voyager 2 are higher compared to Voyager 1 for the period ~1986-1989. For this period protons drift in mostly along the HCS toward Earth. While Voyager 1 travelled to higher latitudes (shown in Figure 2.29), during this period, Voyager 2 stayed close to the equatorial plane and therefore higher intensities are expected, a feature also evident in the computations (see also *Potgieter and Le Roux*, 1992). For the period ~1992-2000 the opposite occurs with intensities along the Voyager 1 higher compared to Voyager 2 with the model also reproducing these features (see also *Ferreira*, 2002).

From the computed intensities, when compared to the spacecraft observations as shown in Figure 9.4, it is evident that in order to predict the future $E > 70$ MeV proton intensities,

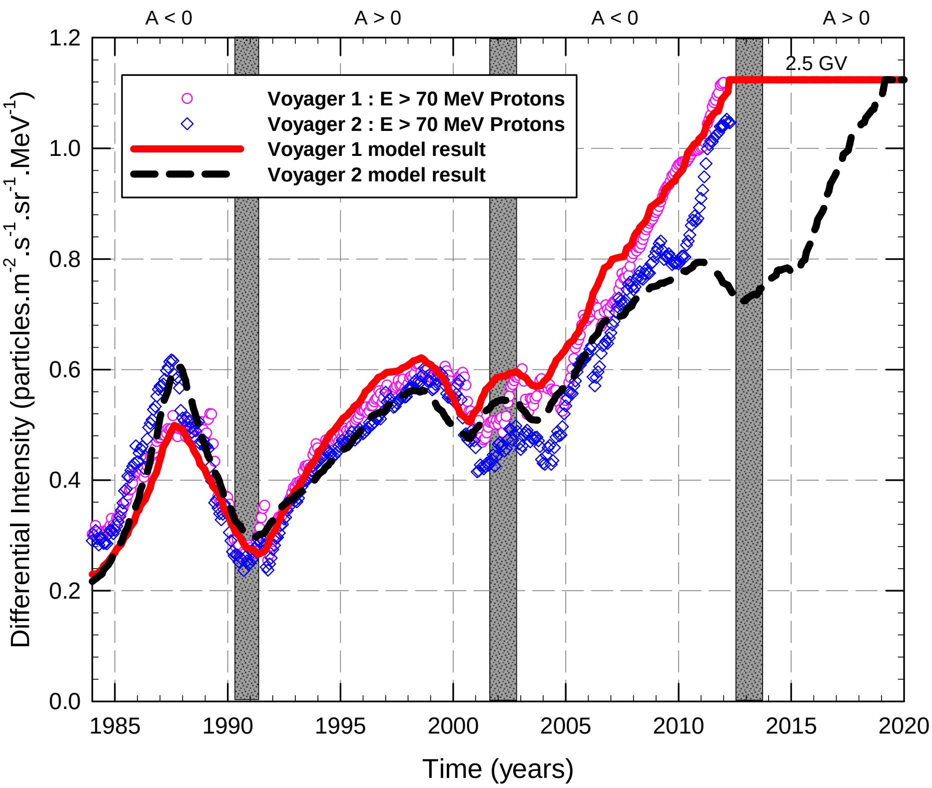

Figure 9.4: Computed 2.5 GV cosmic ray proton intensities along the Voyager 1 and 2 trajectories since 1984. Predicted intensities are shown until the spacecraft reaches the assumed heliopause (modulation boundary in the model). Computations are done for a symmetrical heliosphere. Also shown are the $E > 70$ MeV proton observations from Voyager 1 and 2 (from http://voyager.gsfc.nasa.gov) as symbols (circles and diamonds). The shaded areas represent the periods where there were not a well defined HMF polarity.

especially along the Voyager 2 trajectory an asymmetric heliosphere or a higher HPS, must be assumed. This aspect is tested next. Because the focus is now on the outer heliosphere, the results are shown only from 2004 onwards for Voyager 1 and from 2005 onwards for Voyager 2, when both spacecraft were beyond 70 AU.

9.4 Effect of different heliopause spectra and boundary positions on cosmic ray modulation

In this section the cosmic ray modulation in the outer heliosphere, along both Voyager trajectories, are computed up to 2012 and beyond. A symmetrical heliosphere but with different HPS values are first assumed. Note that the TS position r_{ts} is assumed at 90 AU along the Voyager 1. In the next chapter the effect of a dynamic TS is illustrated. Figure 9.5 shows four different computed scenarios of 2.5 GV cosmic ray proton intensities, along the Voyager 1 trajectory from 2004 until the heliopause (boundary), as a function of time. The red solid line shows the

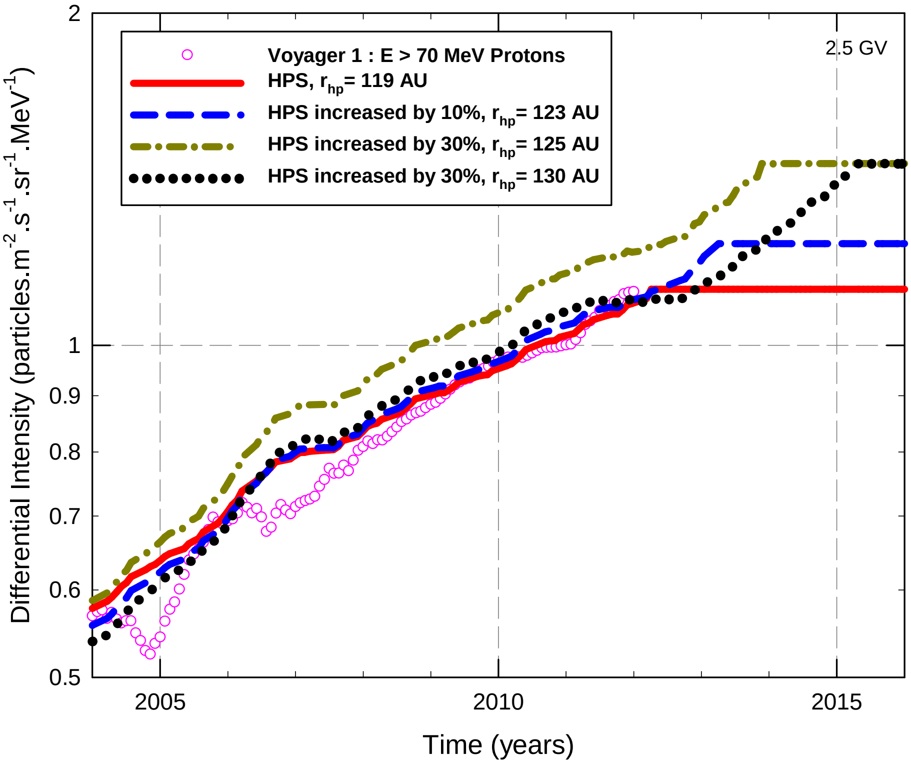

Figure 9.5: Computed 2.5 GV cosmic ray proton intensities along the Voyager 1 trajectory in the outer heliosphere are shown as a function of time for different assumed HPS values and heliopause positions. Also shown are the $E > 70$ MeV proton observations from Voyager 1 (from http://voyager.gsfc.nasa.gov) as symbols. Note that the model computed results only until the heliopause distance, the cosmic ray intensities beyond the heliopause are illustrated as a constant value representing the HPS.

model result corresponding to the HPS level observed at ∼119 AU by the Voyager 1 spacecraft in 2012. This scenario fits the observations on a global scale and a steady increase in proton intensities are computed with no significant solar cycle effects evident in the results since the spacecraft is very close to the modulation boundary. A second scenario is computed by assuming a 10% higher HPS value, as shown by blue dash line. In order to compute a realistic result when compared to observations, the modulation boundary r_{hp} has to be increased from 119 AU to 123 AU for this scenario. Also, for this scenario the computed intensities show no clear solar cycle effects due to the close proximity to the boundary, e.g. reaching it by ∼2013.

A third scenario is shown in Figure 9.5 as a yellow dash-dotted line, which shows a 30% increased HPS value assumed at 125 AU. This scenario computes compatible results when compared to observations from 2004 until 2005, after which the model computed intensities much higher than the observations until reaching the assumed heliopause in ∼2014 at 125 AU. This shows that the assumed r_{hp} for this 30% increased HPS value is possibly larger, e.g. suggesting a larger r_{hp} as shown by black dotted line with r_{hp} at 130 AU. This computed scenario also resulted in compatible results when compared to the observations on a global scale. This

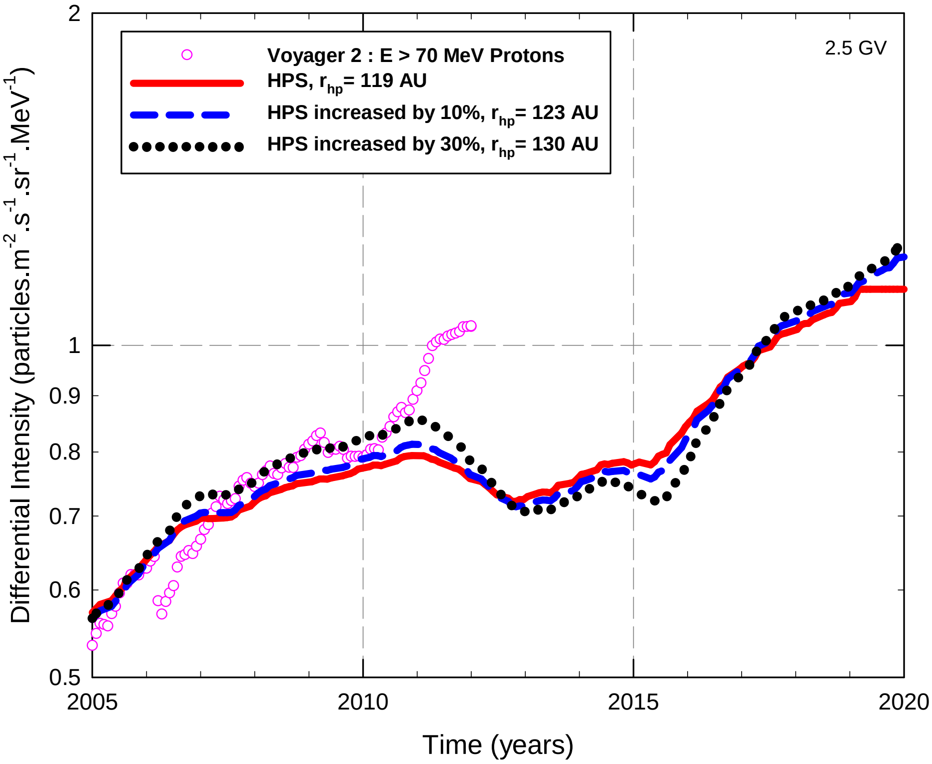

Figure 9.6: Similar to Figure 9.5 except that here modelling results are shown along the Voyager 2 trajectory with the same parameters as used in Figure 9.5.

scenario shows the presence of a solar cycle in the computed intensities as a plateau region for the period ∼2012-2013, and then a steady increase in intensities are computed until reaching the heliopause. The effect of solar cycle is due to the larger modulation volume between the spacecraft and the heliopause. In this case, the distance between the last available observation (∼2012 or ∼119 AU) of Voyager 1 and the assumed boundary is ∼11 AU. Also note that the model fails to reproduce the effect of propagating diffusion barriers seen during the period ∼2005 and ∼2007.

Within the limitations of this model, it is clear that one cannot learn more about the expected value of the HPS at this energy without knowing the exact location of the heliopause and transport parameters. However, the model results indicate that Voyager 1 should measure on average a steady increase in intensities implying a constant radial gradient depending on the value of the HPS and boundary. This steady increase in intensities may not be necessarily true for Voyager 2 which is discussed next (see also *Manuel et al.*, 2011a,b).

Figure 9.6 shows the computed 2.5 GV proton intensities along the Voyager 2 trajectory up to ∼2020, assuming the exact same set of parameters as used along the Voyager 1 trajectory. Different scenarios are shown corresponding to different HPS values as indicated in the legend. The red solid line in the figure represents the scenario with the assumed HPS corresponds

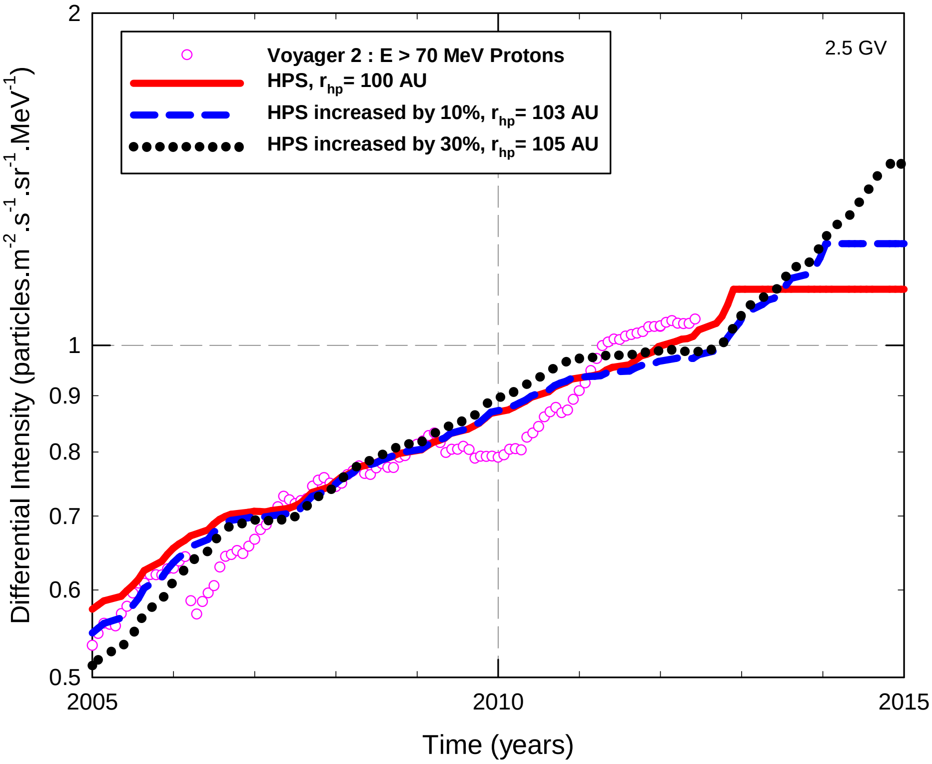

Figure 9.7: Similar to Figure 9.6 except that here optimal modelling scenarios along the Voyager 2 trajectory are shown for different assumed HPS values and heliopause positions.

to the intensity as observed by Voyager 1 at 119 AU. This scenario computes compatible intensities compared to observations until ∼2010, but afterwards intensities lower compared to the observations. Also this scenario shows modulation effects due to the solar cycle because of a large modulation volume (∼21 AU) between the spacecraft and the heliopause. The blue dashed line in Figure 9.6 represents a scenario with the assumed HPS increased by 10% compared to the previous scenario and a boundary assumed at 123 AU. This scenario also computes compatible intensities until ∼2010, but afterwards computed intensities are lower than the observations. A third scenario represented by the black dotted line assumed a 30% increase in the assumed HPS and a boundary located at 130 AU. The result for this scenario also compute realistic intensities that are compatible with observations until ∼2011. However, after ∼2011, the computed intensities deviate from the observations by showing a decrease in intensities while the observations show an increase in cosmic ray proton intensities. These scenarios show that if a symmetrical heliosphere is assumed, a higher HPS than assumed in the model cannot reproduce the cosmic ray proton observations along the Voyager 2 trajectory. Note that in Chapter 8, it was already shown that it is impossible to reproduce cosmic ray observations along both Voyager trajectories if considering a symmetrical heliosphere even with a different set of transport parameters in north and south heliospheric hemispheres. It was suggested that an asymmetrical heliosphere is required to fit the observations if the HPS is the same in both hemispheres. This aspect is again proved in this chapter with different HPS values and boundary scenarios that compute proton intensities beyond 2012 along both Voyager trajectories.

From a thorough parameter study (as shown above and in Chapter 8), e.g. changing the magnitude, radial and latitudinal dependence of the different diffusion coefficients, the value of the drift coefficient, increasing the assumed HPS, etc. it was shown that it is not possible to fit both Voyager 1 and Voyager 2 observations using exactly the same set of parameters in both hemispheres. Figure 9.7 shows computed 2.5 GV proton intensities along the Voyager 2 trajectory when an asymmetrical heliosphere is assumed. The red solid line represents the modelling result with the HPS assumed as that measured by Voyager 1 at ∼119 AU but specified in the model at 100 AU. This result shows that when an asymmetrical heliosphere with smaller modulation boundary (100 AU) is assumed in the southern hemisphere, the computed intensities produced an improved compatibility with the observations, except for the extreme solar maximum periods when the model needs some form of merging of the propagated values from Earth (*Manuel et al.*, 2011c,d). According to this scenario the spacecraft will reach the heliopause by ∼2013, after traversing ∼3 AU from ∼97 AU in 2012. This scenario also shows a steep increase in intensities after ∼2012.5 until reaching the heliopause.

The blue dashed line in Figure 9.7 shows computed 2.5 GV proton intensities along the Voyager 2 when a 10% higher HPS value is assumed at 103 AU. This scenario also generally reproduced the cosmic ray observations along the Voyager 2 trajectory when a smaller r_{hp} position (103 AU) compared to 123 AU is assumed along the Voyager 1. The computations predict that for this HPS the spacecraft will reach r_{hp} in ∼2014. Also, for this scenario solar cycle effects are predicted until ∼2013 and later on a steady increase in intensities until Voyager 2 reaches the boundary. A third scenario, where a 30% higher HPS value is assumed at 105 AU is shown as black dotted line in Figure 9.7. This scenario also reproduced the observations and predicts a steady increase in cosmic ray intensities after ∼2013 until reaching the heliopause in ∼2015. The model predicts that the Voyager 2 spacecraft should measure almost a constant (or decreasing) intensities for a few years (up to ∼2013), whereafter a sharp increase is expected when it is nearing the boundary, similar to what Voyager 1 now observes.

9.5 Comparing modelling results with 133-242 MeV observations

Considering the possible contamination from anomalous cosmic rays in $E > 70$ MeV proton channel (*Stone et al.*, 2008), especially close to the shock, this study also predicts future cosmic ray observations for the 133-242 MeV proton channel for both Voyager spacecraft for consistency. Figure 9.8 shows the computed 200 MeV cosmic ray proton intensities along the Voyager 1 trajectory in the outer heliosphere until reaching the assumed heliopause. The red solid line represents the computed intensities along the Voyager 1 trajectory where the measured 133-242 MeV intensity at ∼119 AU by Voyager 1, is assumed as the HPS value. These computed

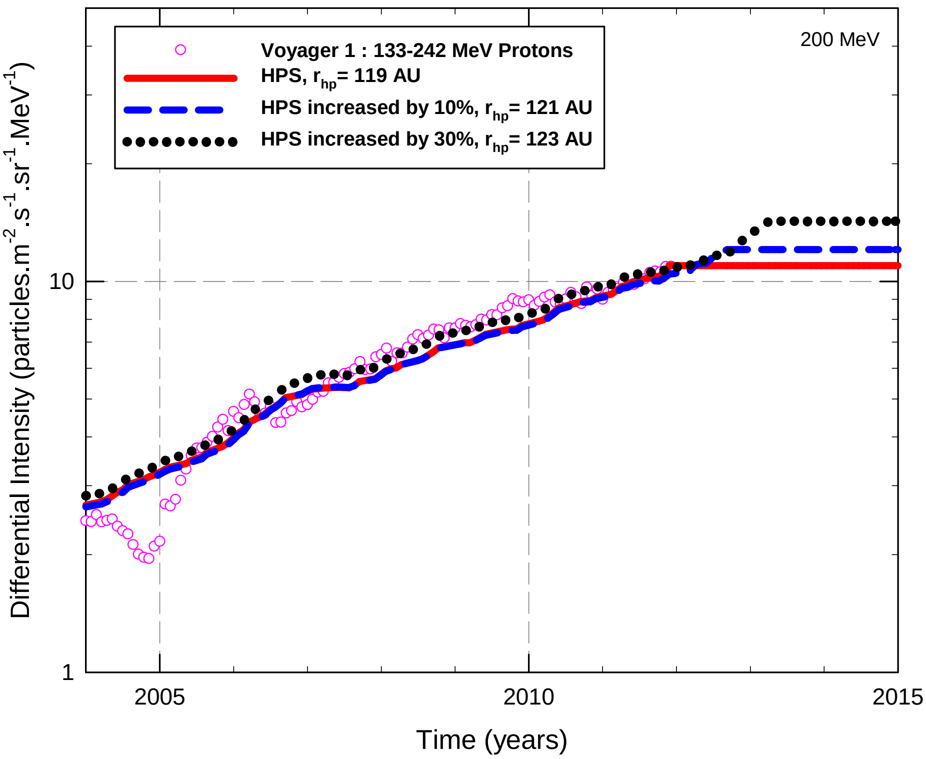

Figure 9.8: Computed 200 MeV cosmic ray proton intensities along the Voyager 1 trajectory are shown as a function of time for different assumed HPS values and heliopause positions. Also shown are the 133-242 MeV proton observations from Voyager 1 (from `http://voyager.gsfc.nasa.gov`) as symbols.

results are compatible to the observations but again fail to reproduce the large decrease at the end of 2004. The second scenario, represented by the blue dashed line, assumes a 10% higher HPS value at this energy and a boundary at 121 AU to produce compatible results along the Voyager 1. This scenario predicts a steady increase in cosmic ray proton intensities until reaching the heliopause in ∼2012.5. A third scenario is also assumed with a 30% higher HPS value and boundary at 123 AU and is shown as a black dotted line. According to this scenario, Voyager 1 will reach the heliopause in ∼2013 showing a small solar cycle effect after ∼2012 and afterwards a steady increase in intensities until reaching the heliopause. When compared to 2.5 GV result (see Figure 9.5) this 200 MeV result needs a 2 AU smaller heliopause position for a 10% higher HPS value and a 7 AU smaller heliopause position for a 30% higher HPS value to compute optimal results.

Figure 9.9 shows the computed 200 MeV cosmic ray proton intensities along the Voyager 2 trajectory from 2005 until reaching the assumed heliopause position. Results are again compared to the 133-242 MeV observed proton intensities by Voyager 2. The red solid line shows the computed intensities when an HPS value, as observed by Voyager 1 at ∼119 AU is assumed at 99 AU along the Voyager 2 trajectory. The model computed compatible results when compared to the observations on a global scale but fails to reproduce the large decrease at the end of 2004.

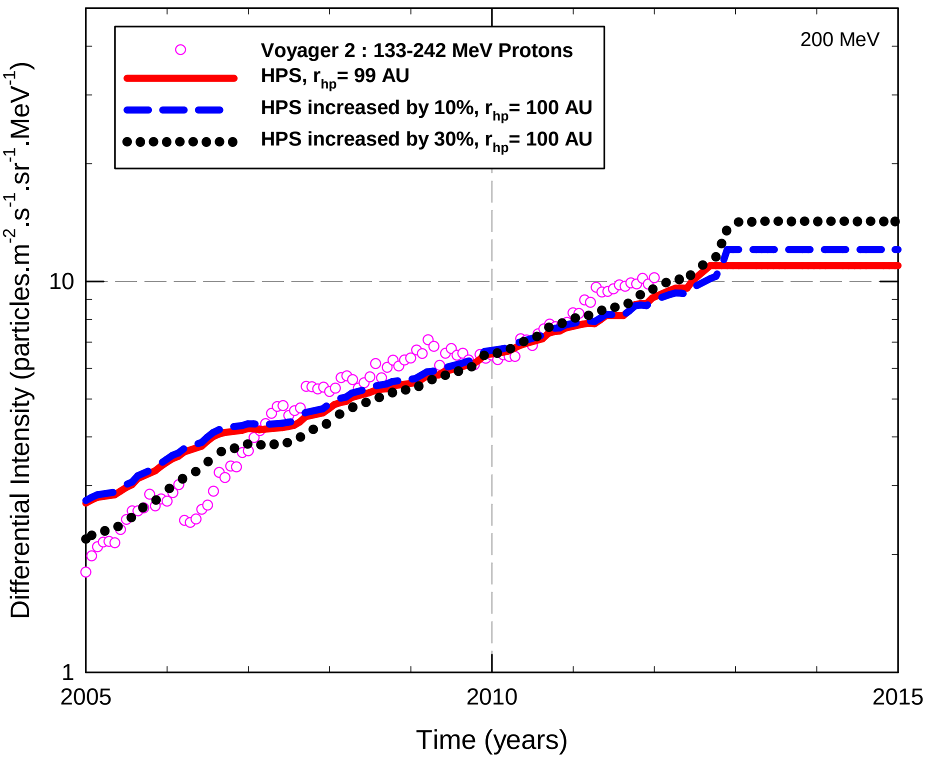

Figure 9.9: Similar to Figure 9.8 except that here optimal modelling results along the Voyager 2 trajectory are shown for different assumed HPS values.

For this scenario, the model predicts that Voyager will reach the heliopause by ∼2012.7 computing a steady increase in intensities until reaching the boundary. The blue dashed and black dotted lines represent the scenarios where 10% and 30% higher HPS values are assumed at 100 AU. Both the scenarios computed compatible results and show a steady increase until ∼2012.7 and then a steep increase in intensities are computed until reaching the heliopause in ∼2013 and ∼2014 respectively. This again suggests, as discussed above, that without knowing the true HPS or location of heliopause and transport parameters, one could not make exact prediction of cosmic ray intensities along both the Voyagers. However, possible different scenarios of future cosmic ray intensities along these spacecraft could be computed for the assumed different HPS and heliopause positions.

By comparing Figures 9.8 and 9.9 to 9.5 and 9.7 respectively, it follows that the computations when compared to observations at different energies, result in the same conclusions.

9.6 Summary and conclusions

In this chapter, various scenarios were computed predicting possible future $E > 70$ MeV cosmic ray proton intensities along the Voyager 1 and Voyager 2 spacecraft trajectories. For this purpose, the input parameters, such as the tilt angle, HMF magnitude and total variance as from the ∼1987 solar minimum were assumed to compute predicted intensities. It was shown that the model computed compatible intensities on a global scale, when compared to observations, but needs some improvements for extreme solar conditions (large intensity changes) where merging of interaction regions seems necessary. It was found that for a symmetric heliosphere, with the same set of diffusion parameters and HPS values in both hemispheres, the computations along the Voyager 2 trajectory were incompatible with the observations especially after ∼2010. A symmetrical heliosphere with different HPS values assumed at the boundary in both hemispheres also resulted in incompatible results. This suggests that an asymmetrical heliosphere (with the same HPS in both hemispheres) is necessary to simulate the Voyager observations.

The predicted cosmic ray intensities along the Voyager 1 indicate that this spacecraft should be relatively close to the heliopause so that the computed intensities increase with an almost constant rate. However, the model shows that Voyager 2 is still under the influence of temporal solar activity changes because of a large distance to the heliopause when compared to Voyager 1. Furthermore, the model predicts that along the Voyager 2 trajectory, the intensities may remain generally constant (with temporal effects superimposed) for the next few years and then will start to steadily increase as in the case of present Voyager 1 observations.

Model results at a lower energy, i.e. 200 MeV, were also computed and compared with a lower energy channel (133-242 MeV) on-board the Voyagers. This resulted in the same conclusion as when results were compared to the $E > 70$ MeV channel. Also, this investigation shows that without knowing the exact location of the heliopause and the transport parameters one could not conclude anything about the HPS value at these energies.

In the next chapter, a dynamic TS position will be implemented in the numerical model and then cosmic ray intensities along both Voyagers will be computed to show the effect of such a time-varying inner heliosheath thickness.