Chapter 10

Effect of a dynamic inner heliosheath on cosmic ray modulation in the outer heliosphere

10.1 Introduction

In the previous chapter, predictions for $E > 70$ MeV and 133-242 MeV protons intensities were calculated along the Voyager 1 and 2 spacecraft trajectories for time periods up to 2012 and beyond. In this chapter, the effect of a changing TS radius (dynamic inner heliosheath) on cosmic ray modulation along both Voyager spacecraft trajectories is investigated. A time-dependent TS radius, as proposed by *Snyman* (2007) and *Webber and Intriligator* (2011), is introduced into the numerical transport model (discussed in Chapter 4) and calculations are compared to Voyager observations. Note that only the shock position is varied over time. Other properties such as the compression ratio which also change over a solar cycle (*Scherer et al.*, 2006a) were not considered. See also the discussion by *Ngobeni and Potgieter* (2011, 2012).

It is shown that a changing TS radius alone does not significantly improve the compatibility between modelling results and Voyager observations, as those already shown in the previous chapters. However, a time-dependent TS position along with a time-dependent heliopause position could lead to improved compatibility between model and Voyager observations. The assumed time-dependence in heliopause position is similar to that of the TS because the ratio of the heliopause and TS positions is assumed constant as proposed by *Muller et al.* (2006, 2009). This work suggests that the time-dependence in the TS position (and the heliopause position) as proposed by *Snyman* (2007) and *Webber and Intriligator* (2011) can lead to improved compatibility with the observations. The ratio between heliopause and TS position is taken as 1.35 along the Voyager 1 trajectory and as 1.2 along the Voyager 2 trajectory up to ∼2010, similar to what *Muller et al.* (2006, 2009) proposed. However, after 2010 and until 2012 the transport model predicts a nearly unchanged heliopause and TS radius when results are compared to observations, with the heliopause and TS at ∼119 AU and ∼88 AU along the Voyager 1 trajectory and at ∼100 AU and ∼84 AU along the Voyager 2 trajectory. This indicates that if a time-dependence in the heliopause exists, the amplitude between solar minimum and maximum should be smaller compared to the TS.

10.2 The dynamic heliosphere

The heliosphere is a dynamic structure which formed due to the interaction of the solar wind with LISM. The boundary regions e.g. the TS, heliopause and bow shock/wave are formed due to this interaction and change position over time to form a dynamic heliosheath. The oscillations of these boundaries respond to variations of the solar wind speed and solar wind density which change over a ∼11 year solar cycle (*Scherer and Fahr*, 2003b). An increase in either the density or the velocity of the solar wind (or LISM) would result in a TS, heliopause and bow shock/wave to form at larger (or smaller in the case of LISM density or velocity increase) heliocentric distances (see e.g. *Whang et al.*, 1995; *Wang and Belcher*, 1999; *Scherer and Fahr*, 2003b; *Whang et al.*, 2004; *Scherer and Ferreira*, 2005a,b; *Snyman*, 2007; *Richardson and Wang*, 2011; *Washimi et al.*, 2011).

Whang et al. (1995) proposed that the location of the TS is anti-correlated with the sunspot number i.e. the TS radius is located further away from the Sun during solar minimum periods and is located near the Sun during solar maximum periods. Later, *Wang and Belcher* (1999) proposed that the location of TS oscillates about 13 AU per solar cycle in response to the ∼11 year solar cycle and it moves outwards faster than it moves inwards. These authors also suggested that the heliopause excursions are about 6 AU per solar cycle and the bow shock is unaffected by any variations due to solar cycle. However, *Whang et al.* (2004) later suggested a ∼50 AU oscillating TS near 35^o heliographic latitude. As shown by *Scherer and Ferreira* (2005a,b) using a hybrid numerical model (which combines a hydrodynamic model and a cosmic ray transport model), changes in the geometry of the heliosphere also influence cosmic ray particle distribution inside the heliosphere.

Observations by both Voyager spacecraft confirmed the existence of a dynamic TS. During the Voyager 1 TS crossing, the TS was moving inwards towards the Sun (*Stone et al.*, 2005). However, during Voyager 2 TS crossing period, the TS was moving outwards with respect to the Sun and remained near the spacecraft for nearly a year and then moved inwards rapidly towards the Sun (*Richardson and Wang*, 2011). A TS position 10 AU closer to the Sun along the Voyager 2 trajectory, compared to the Voyager 1, suggests a possible asymmetric structure of the TS and/or a time-dependence in TS position.

Recent work done by *Snyman* (2007), *Webber and Intriligator* (2011), *Richardson and Wang* (2011) and *Washimi et al.* (2011) computed the time-dependent profile of the TS radius from the Sun using various models. For example *Washimi et al.* (2011) computed the TS position using a 3D magnetohydrodynamic model which includes the effect of neutral particles and *Richardson and Wang* (2011) computed the TS position using a 2D hydrodynamic model which includes the effect of pickup ions. The former authors used Voyager 2 observations while the latter

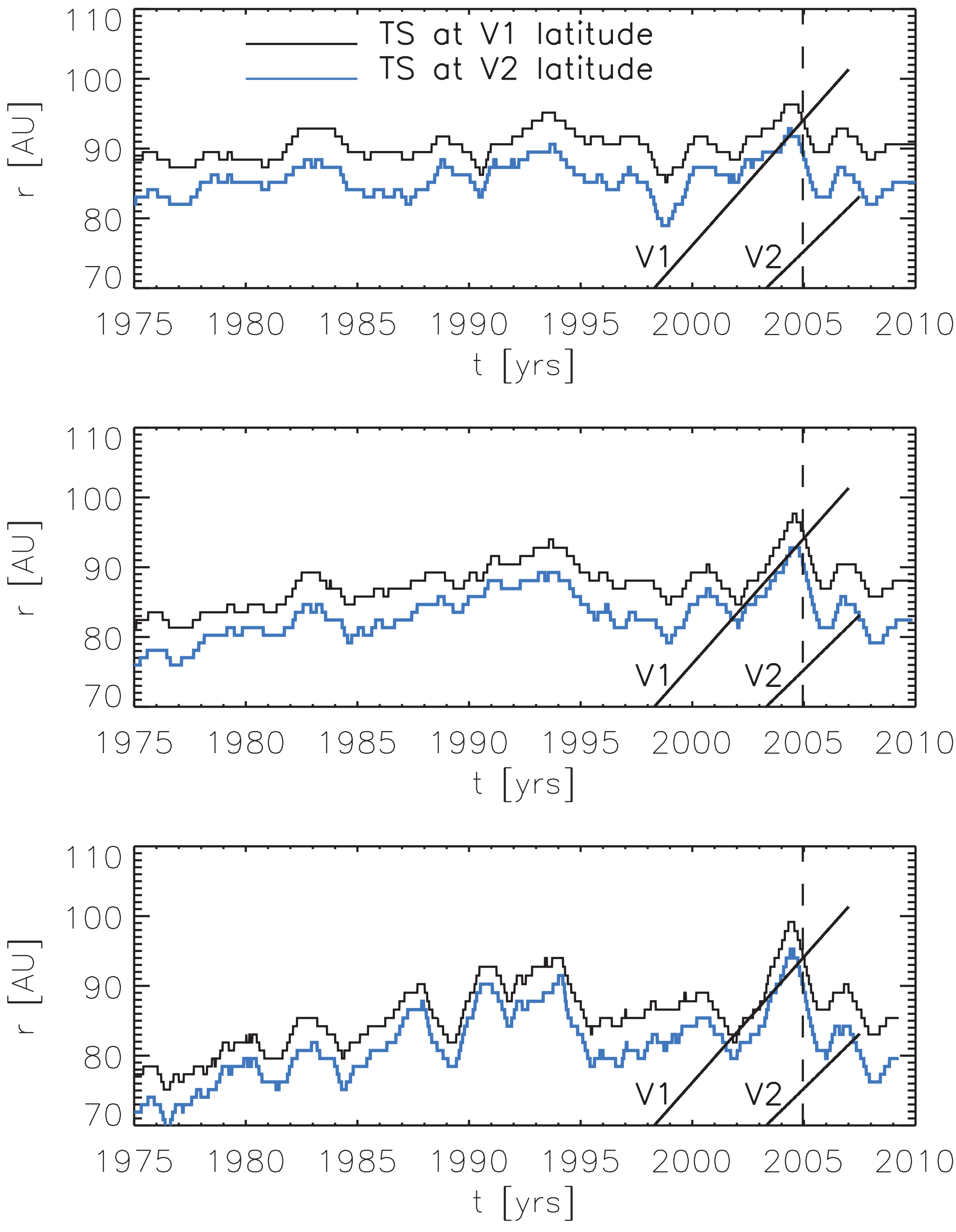

Figure 10.1: The computed positions of TS distance from the Sun at 34.1^o heliographic latitude (solid black lines) and at -27^o heliographic latitude (solid blue lines). The top, middle and bottom panels show the TS positions computed from lower, mean and upper limit values of the solar wind speed, density and pressure observations from various spacecraft. Also shown are the trajectories of the Voyager 1 and Voyager 2 spacecraft in terms of radial distance from the Sun (thick black lines). The vertical dashed lines represent the Voyager 1 TS crossing period. From *Snyman* (2007).

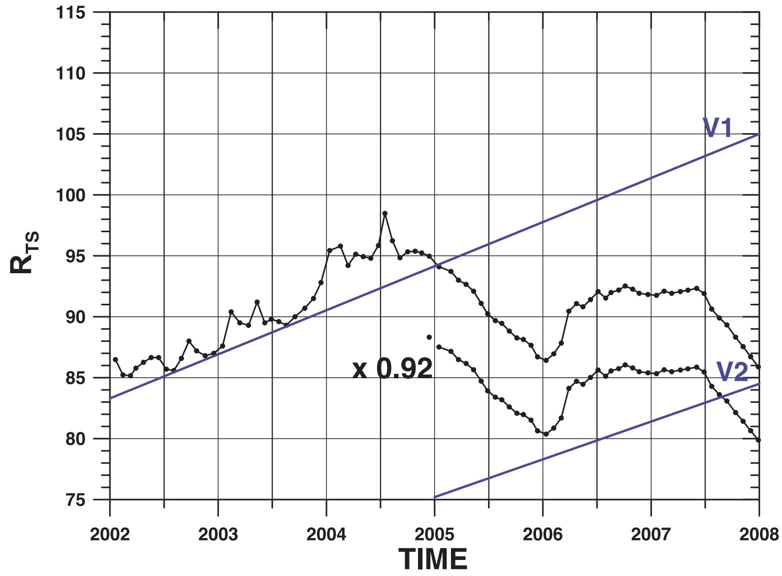

Figure 10.2: The computed position of the TS (in AU) along the Voyager 1 trajectory for the period 2002-2008 and along the Voyager 2 trajectory for the period 2005-2008. The TS distance along Voyager 2 is computed by normalising the TS along the Voyager 1 trajectory such that it corresponds to the Voyager 2 TS crossing at 2007.7. Also shown are the trajectories of Voyager 1 and Voyager 2 spacecraft in terms of radial distance from the Sun (thick blue lines). From *Webber and Intriligator* (2011).

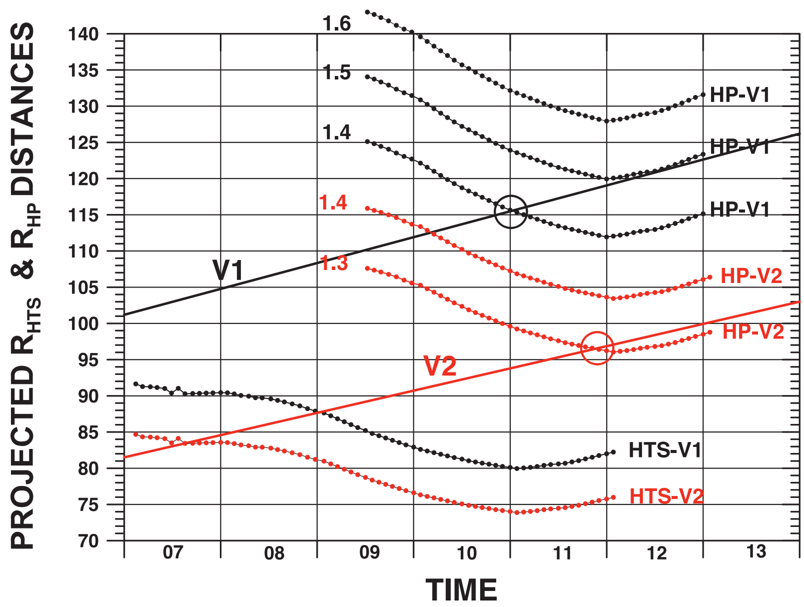

Figure 10.3: The computed distance (in AU) to the TS along the Voyager 1 trajectory (HTS-V1, black dotted lines) and along the Voyager 2 trajectory (HTS-V2, red dotted lines) for the period 2007-2012. Also shown are the computed distance (in AU) to the heliopause assuming the ratio of the heliopause distance to the TS distance, delayed by 1 year, remains constant with time with values between 1.4 and 1.6 along the Voyager 1 trajectory (HP-V1, black dotted lines) and between 1.3 and 1.4 along the Voyager 2 trajectory (HP-V2, red dotted lines). Also shown are the trajectories of Voyager 1 and Voyager 2 spacecraft in terms of radial distance from the Sun (thick black and red lines). Circles represent the heliopause crossing of both spacecraft. From *Webber and Intriligator* (2011).

used Voyager 2 observations along with OMNI observations to calculate the time-dependent TS position. However, for this study calculations by *Snyman* (2007) and *Webber and Intriligator* (2011) are used and discussed below.

Using a 2D hydrodynamic model which describes the solar wind interaction with the LISM, *Snyman* (2007) studied the heliosphere both as a steady-state and dynamic structure. He showed that any short term variations in solar wind density and velocity will induce waves of increased and decreased dynamic pressure in the solar wind and the position of the TS will move inwards or outwards with respect to the Sun in response to these changes. Figure 10.1 by *Snyman* (2007) shows the computed positions of the TS distance from the Sun at 34.1^o heliographic latitude (solid black lines) and at -27^o heliographic latitude (solid blue lines). The top, middle and bottom panels show the TS positions computed using lower, mean and upper limit values of different spacecraft observations of the solar wind speed, density and pressure as boundary conditions. Also shown are the trajectories of the Voyager 1 and Voyager 2 spacecraft in terms of radial distance from the Sun (thick black lines). The vertical dashed lines represents the period when Voyager 1 crossed the TS.

The computed TS positions in all three cases in Figure 10.1 show that as Voyager 1 approached the TS during 2002, the TS was moving outwards with respect to the Sun. The computed position of TS which used lower limit values of the different spacecraft observations (top panel) as boundary conditions in the model show that from ∼2002 onwards the spacecraft is moving outwards faster than the TS and approaches the TS in ∼2005. For the same period, the model which used the mean observed values (middle panel) as boundary conditions, computed that the TS is moving away from the spacecraft until ∼2004 and later moves backwards towards the spacecraft for the crossing in ∼2005. However, the last scenario which used upper limit values of the different spacecraft observations (bottom panel) shows multiple TS crossings by the Voyager 1 spacecraft from ∼2002 to ∼2003 and then the TS moves outwards and away from the spacecraft at a faster speed until ∼2004 and return backwards for the TS crossing in ∼2005. However, the Voyager 2 TS crossing is computed at 2007.7 for all three scenarios when TS moves inwards towards the Sun.

Recently, *Webber and Intriligator* (2011) also computed a TS distance as a function of time along both Voyager trajectories using the solar wind plasma data from Voyager 2 for the period until the Voyager 2 TS crossing (i.e. until 2007) and later from 2007 onwards they used the plasma data at 1 AU from the Solar Wind Electron, Proton and Alpha Monitor (SWEPAM) instrument on ACE and the OMNI plasma data for the period. The plasma data from above-mentioned spacecraft were used to compute the solar wind ram pressure and this pressure was used then to calculate the location of the TS (see also *Webber*, 2005).

Figure 10.2 shows the computed position of TS (in AU) along the Voyager 1 trajectory for the period 2002-2008 and along the Voyager 2 trajectory for the period 2005-2008 by *Webber and Intriligator* (2011). The TS distance along the Voyager 1 is first computed by these authors and then the TS distance along the Voyager 2 by normalising the TS distance along the Voyager 1 trajectory (e.g. by multiplying with 0.92) such that it corresponds to the Voyager 2 TS crossing at 2007.7. Also shown are the trajectories of the Voyager 1 and Voyager 2 spacecraft in terms of radial distance from the Sun (thick blue lines).

The computed distance (in AU) to the TS along the Voyager 1 trajectory (HTS-V1, black dotted lines) and along the Voyager 2 trajectory (HTS-V2, red dotted lines) for the period 2007-2012 by *Webber and Intriligator* (2011) is shown in Figure 10.3. Also shown are the computed distance (in AU) to the heliopause assuming the ratio of the heliopause distance to the TS distance (delayed by 1 year) remains constant with time. Different scenarios corresponding to different ratios, between 1.4 and 1.6, are shown along the Voyager 1 trajectory (HP-V1, black dotted lines) and different scenarios corresponding to different ratios, between 1.3 and 1.4, are shown along the Voyager 2 trajectory (HP-V2, red dotted lines). The trajectories of the Voyager 1 and Voyager 2 spacecraft in terms of radial distance from the Sun (thick black and red lines) are also shown. Circles represent the heliopause crossing of both spacecraft. The time-dependent TS position implemented in this model and used in this study is discussed next.

10.3 Time-dependent termination shock position

To study the effect of a dynamic inner heliosheath on cosmic ray modulation, the time-dependent TS positions along both Voyager trajectories as proposed by *Snyman* (2007) and *Webber and Intriligator* (2011) are assumed as possible scenarios for this study. These time-dependent TS positions are used as additional input parameters in the model along with those discussed in previous chapters to compute cosmic ray intensities along both Voyager trajectories. Note that for this work, only the period from 2002 to 2012, when both Voyagers were in the outer heliospheric regions, are studied. Figure 10.4 shows the time-dependent TS positions along the Voyager 1 and Voyager 2 trajectories as proposed by *Snyman* (2007). The computed results by *Snyman* (2007), as shown in Figure 10.1, are smoothed (to eliminate numerical instabilities in the model) and then extrapolated after 2010 until 2012. This is because the calculation of *Snyman* (2007) ended in 2010. The TS position along the Voyager 1 trajectory is extrapolated from 2010 such that the TS moves inwards towards the Sun from ∼88 AU to ∼84 AU in 2012 and along the Voyager 2 trajectory the TS is extrapolated so the TS move inwards from ∼82 AU to ∼79 AU in 2012.

The position of the TS as a function of time along both Voyager trajectories as proposed by *Webber and Intriligator* (2011) is shown in Figure 10.5. The computed results by *Webber and Intriligator* (2011), as shown in Figures 10.2 and 10.3, are smoothed from 2002 until 2012. For the period 2010 onwards, the TS along the Voyager 1 trajectory moves inwards towards the Sun from ∼83 AU to ∼80 AU in ∼2011 and then moves outwards to ∼82 AU in 2012. Also for the same period the TS along the Voyager 2 trajectory moves inwards towards the Sun from ∼77 AU to ∼74 AU in ∼2011 and then moves outwards to ∼76 AU in 2012. When compared to the *Snyman* (2007) TS scenario, the *Webber and Intriligator* (2011) TS scenario is closer to the

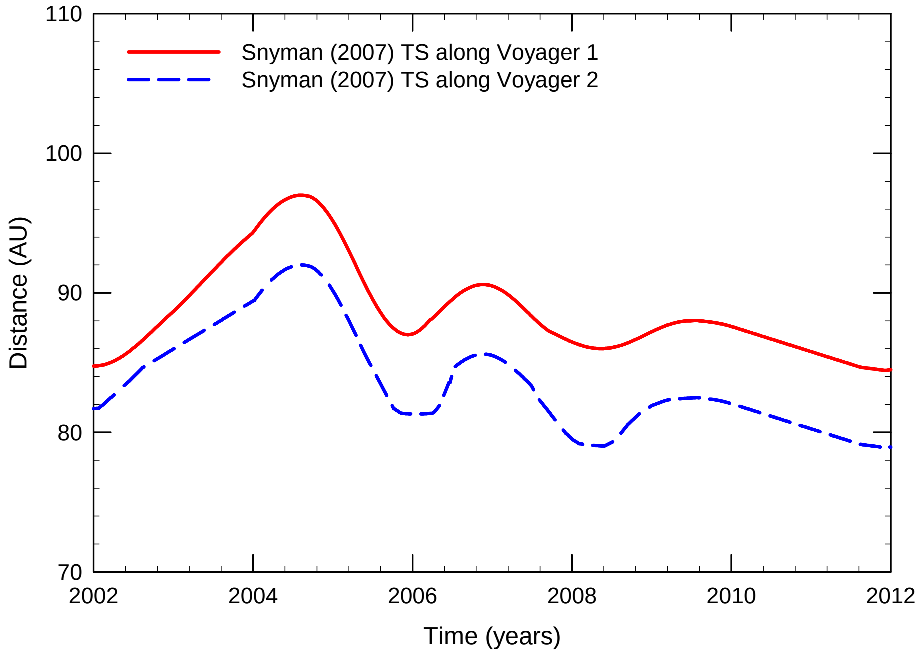

Figure 10.4: The time-dependent TS positions along the Voyager 1 and Voyager 2 trajectories as proposed by *Snyman* (2007). The computed results by *Snyman* (2007) are smoothed and then extrapolated after 2010 until 2012.

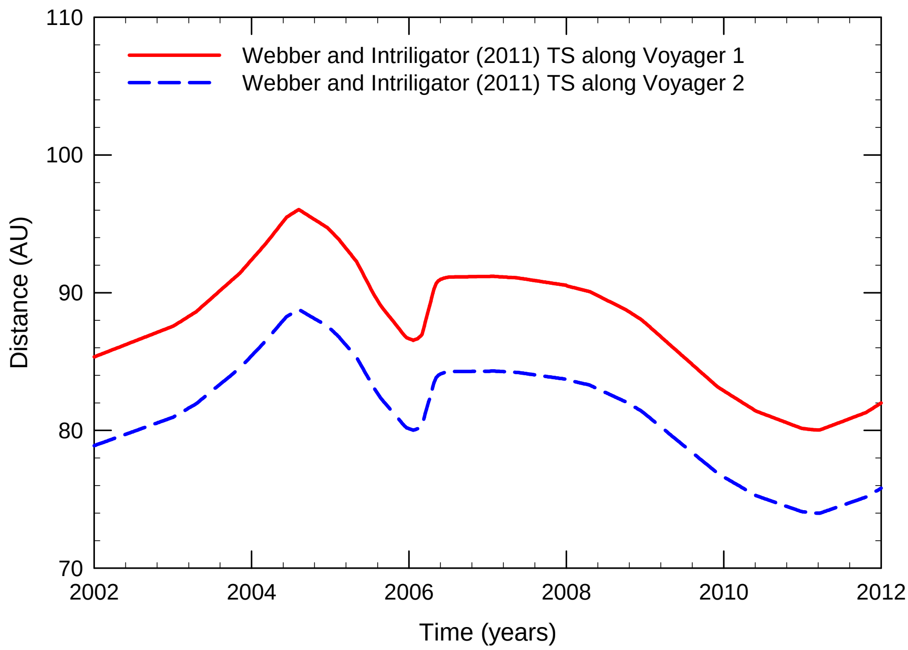

Figure 10.5: The time-dependent TS positions along the Voyager 1 and Voyager 2 trajectories as proposed by *Webber and Intriligator* (2011). Their computed results are smoothed from 2002 until 2012.

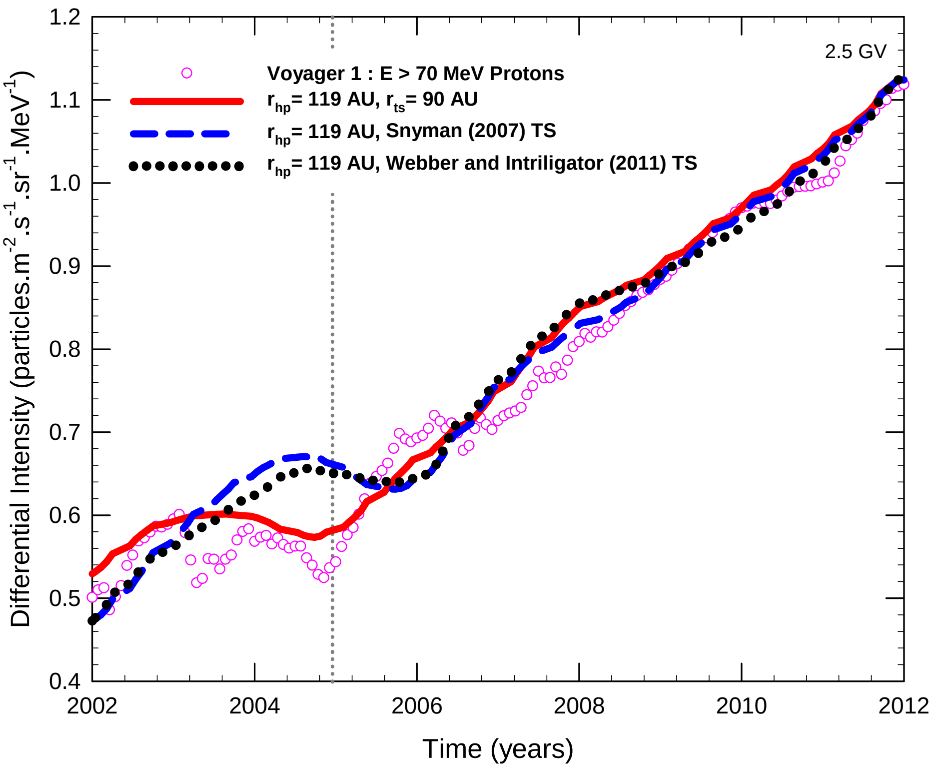

Figure 10.6: Computed 2.5 GV cosmic ray proton intensities along the Voyager 1 trajectory as a function of time since 2002. Results are first shown for an assumed heliopause radius, r_{hp}, at 119 AU and with a static TS position, r_{ts}, at 90 AU. Also shown are model results including a time-dependent r_{ts} as proposed by *Snyman* (2007) and a time-dependent r_{ts} according to *Webber and Intriligator* (2011). The $E > 70$ MeV proton observations from Voyager 1 (data from `http://voyager.gsfc.nasa.gov`) are shown as symbols (circles). The vertical thin dotted line represents the Voyager 1 TS crossing period.

Sun along both spacecraft trajectories. Also both scenarios show similar profiles until ∼2007 but afterwards both differ significantly in the manner the TS moves away or towards the Sun.

10.4 Modelling results along the Voyager 1 trajectory

Figure 10.6 shows the computed 2.5 GV cosmic ray proton intensities along the Voyager 1 trajectory corresponding to a steady-state (static) TS assumed in the model and two time-dependent (dynamic) TS scenarios as proposed by *Snyman* (2007) and *Webber and Intriligator* (2011). The different scenarios are represented as a red solid line (static), blue dashed line (*Snyman*, 2007) and black dotted line (*Webber and Intriligator*, 2011) respectively. Computed results are compared to the $E > 70$ MeV proton observations from Voyager 1, shown as circle symbols. From the figure, it follows that the steady-state TS scenario assumed at 90 AU (red solid line) fits the observations on a global scale as concluded in earlier chapters. However, this scenario failed to reproduce the detail in the observations especially during periods ∼2003, ∼2005 and ∼2007-2008 where step-like decreases were observed and the model computed intensities higher than the observations. For the period around ∼2006 lower intensities were computed

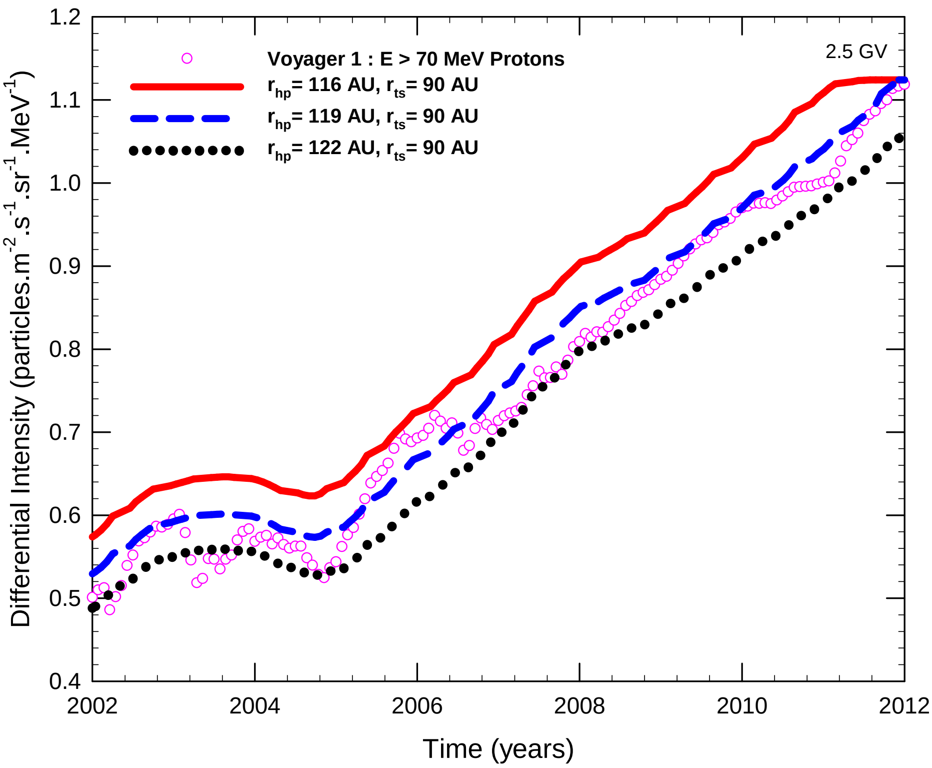

Figure 10.7: Computed 2.5 GV cosmic ray proton intensities along the Voyager 1 trajectory since 2002 are shown as a function of time for different assumed heliopause radii, r_{hp}, and with a static TS position, r_{ts}, at 90 AU. Also shown are the $E > 70$ MeV proton observations from Voyager 1 (data from http://voyager.gsfc.nasa.gov) as symbols (circles).

compared to the observations.

To establish if a dynamic TS position in the model could lead to improved compatibility with the observations, the time-dependent TS scenarios as proposed by *Snyman* (2007) and *Webber and Intriligator* (2011) are implemented into the model and results shown in Figure 10.6. The figure shows that both the scenarios computed similar results which are globally compatible to the observations apart from the period ∼2003-2005. Here the model computed higher intensities compared to observations for both scenarios. It seems that the computed intensities for both TS scenarios are out of phase with the observations during the period ∼2003-2005.

The failure of these time-dependent TS scenarios to reproduce a fit to the ∼2003-2005 period could be interpreted as due to the assumption of a steady-state (static) heliopause position, at 119 AU in the model. For example, the TS position was at ∼94 AU along the Voyager 1 trajectory during ∼2005 (for both TS scenarios), and due to the TS moving outward from ∼2004 to ∼2005 the inner heliosheath thickness is reduced for this period so that the computed cosmic ray intensities are increasing instead of the observed decrease. Also shown in Figure 10.6 is that the effect of a time-dependent TS position is only important as long as the spacecraft was close to the TS position and vanished after ∼2008 until the spacecraft reaches the assumed heliopause at 119 AU in 2012.

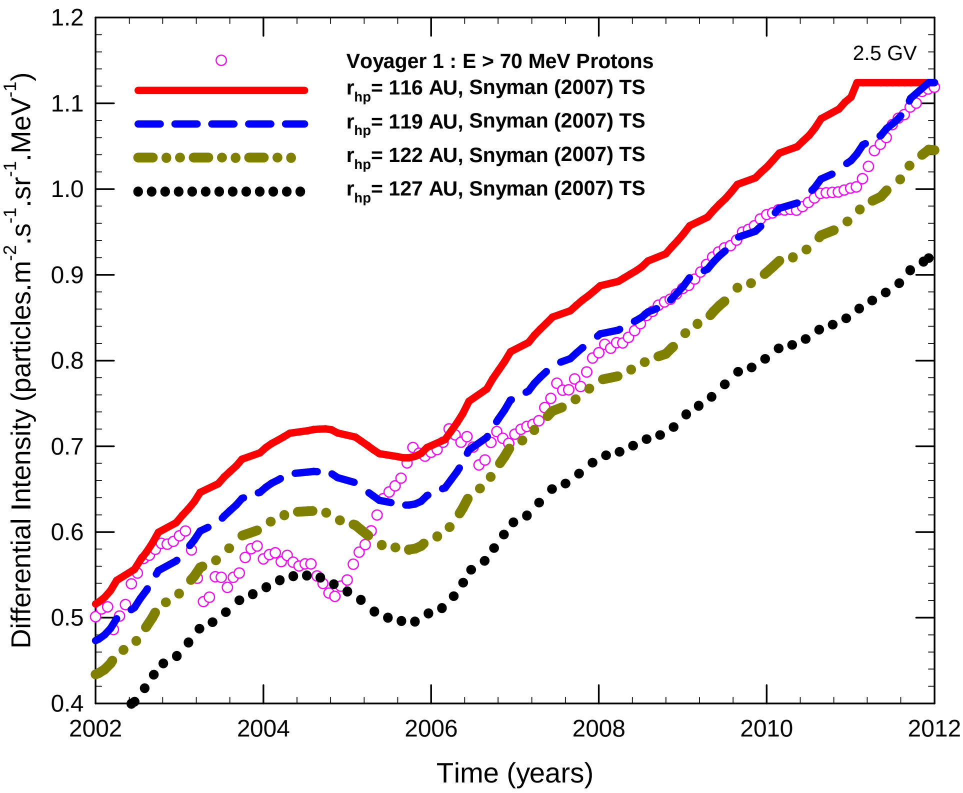

Figure 10.8: Computed 2.5 GV cosmic ray proton intensities along the Voyager 1 trajectory since 2002 are shown as a function of time for different assumed heliopause radii, r_{hp}, and with a time-dependent TS position, r_{ts}, proposed by *Snyman* (2007). Also shown are the $E > 70$ MeV proton observations from Voyager 1 (from `http://voyager.gsfc.nasa.gov`) as symbols (circles).

Not included in the computations in Figure 10.6 is a dynamic (moving) modulation boundary, as proposed by e.g. *Webber and Intriligator* (2011). However, due to the numerical scheme and static computational grid in the model (as discussed in Chapter 4) including such a modulation boundary is beyond the scope of this study. Considering the limitation of the model to include a time-dependent heliopause position, different static heliopause positions are now assumed along with a dynamic TS and the results are compared with observations for compatibility.

In order to test indirectly the effect of a possible time-dependent heliopause position on cosmic ray modulation, first a TS is assumed at 90 AU to show how cosmic ray intensities will respond to a time-dependent heliopause. Figure 10.7 shows the computed cosmic ray intensities for an assumed TS distance at 90 AU with a heliopause distance of 116 AU, 119 AU and 122 AU respectively. From the figure it follows that the heliopause distance of 116 AU (red solid line) fit the observations in ∼2006. The 119 AU heliopause distance (blue dashed line) fit the observations during ∼2003, ∼2010 and ∼2012 respectively. The 122 AU heliopause position (black dotted line) fit the observations during ∼2002, ∼2005, ∼2008 and ∼2011. From this, it follows that in order to fit the cosmic ray observations along the Voyager 1 trajectory in more detail, a heliopause distance which varies between ∼116 AU to ∼122 AU could be included as a time-varying parameter (i.e. a heliopause position which oscillates with an amplitude of ∼3

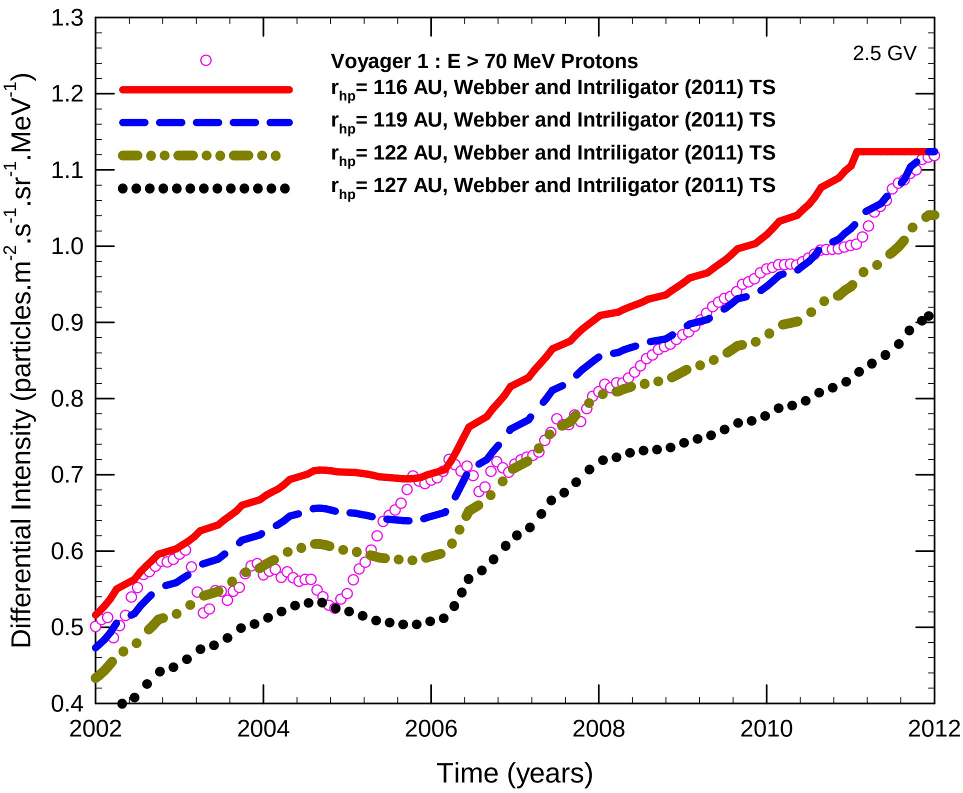

Figure 10.9: Similar to Figure 10.8 except that here modelled results are shown for a time-dependent TS position, r_{ts}, proposed by *Webber and Intriligator* (2011).

AU with respect to ~119 AU).

Figure 10.8 shows the computed cosmic ray intensities along the Voyager 1 trajectory when a time-dependent TS radius, as proposed by *Snyman* (2007), is considered, but with different heliopause positions. From the figure, it follows that during the period ~2002-2003 when TS was located at ~85 AU and increasing towards ~90 AU, a heliopause at 116 AU (red solid line) fits the observations. Also this heliopause scenario fits the observations during ~2006 when the TS was also located at ~85 AU. The blue dashed line represents a scenario with a heliopause located at 119 AU. This scenario fits the observations during ~2003, ~2008-2010 and ~2011-2012. The yellow dashed-dotted line represents a heliopause distance of 122 AU which fits the observations during the period ~2007-2008. The black dotted line represents a heliopause position of 127 AU which fits the observations during ~2005 when the TS position was further away from the Sun and located at ~94 AU.

From all the four scenarios, it follows that when a time-dependent TS radius, as proposed by *Snyman* (2007), is considered in the model, a time-dependent heliopause position which vary between 119 AU to 122 AU (with 116 AU to 127 AU as extreme values in Figure 10.8) is required to fit the observations (*Krimigis et al.*, 2011). The figure also shows that during the period ~2002-2005 (~3 years) the heliopause position could vary from 116 AU to 127 AU, in response to the solar cycle, while TS position varies from ~85 AU to ~95 AU. However, these

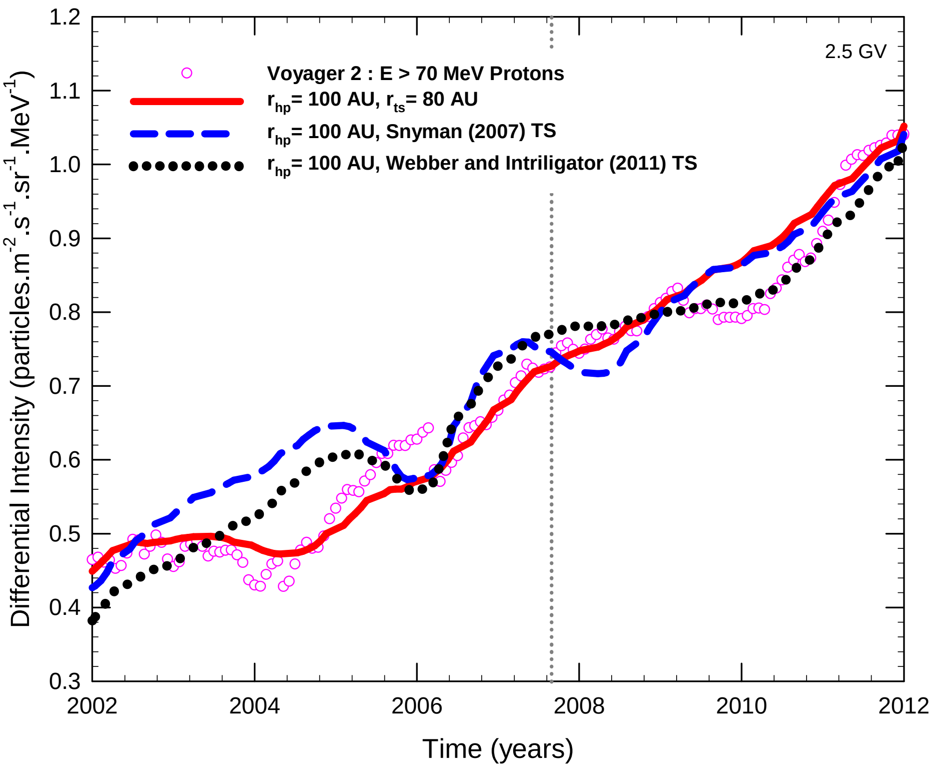

Figure 10.10: Computed 2.5 GV cosmic ray proton intensities along the Voyager 2 trajectory as a function of time since 2002. Results are first shown for the assumed heliopause radius of $r_{hp} = 100$ AU and with a static TS position, $r_{ts} = 80$ AU. Also shown are modelling results including a time-dependent r_{ts} as proposed by *Snyman* (2007) and a time-dependent r_{ts} according to *Webber and Intriligator* (2011). The $E >$ 70 MeV proton observations from Voyager 2 (from `http://voyager.gsfc.nasa.gov`) are shown as circles. The vertical thin dotted line represents the Voyager 2 TS crossing period.

values should be considered too extreme. The heliopause is found to move faster inwards from 127 AU to 116 AU during the period ∼2005-2006 (∼1 year) when the TS moved from ∼95 AU to ∼85 AU.

The computed cosmic ray intensities along the Voyager 1 trajectory for different heliopause positions namely 116 AU, 119 AU, 122 AU and 127 AU using the time-dependent TS positions proposed by *Webber and Intriligator* (2011) are shown in Figure 10.9. All the four scenarios shown in the figure computed similar results as the time-dependent TS scenario proposed by *Snyman* (2007) until ∼2007. This is because the time-dependent TS positions proposed by *Snyman* (2007) and *Webber and Intriligator* (2011) along the Voyager 1 trajectory are similar until ∼2007 but thereafter the TS profiles differ considerably until 2012 (see Figures 10.4 and 10.5). However, after the period ∼2007 until ∼2009 all four scenarios in Figure 10.9 computed higher intensities when compared to the scenarios in Figure 10.8 which used the *Snyman* (2007) TS. However, during the period ∼2009-2011 lower intensities were computed by the scenarios which used *Webber and Intriligator* (2011) TS when compared to *Snyman* (2007) TS results. After ∼2011 for the 119 AU heliopause scenario the effect of the TS is negligible since the spacecraft is close to the modulation boundary (heliopause).

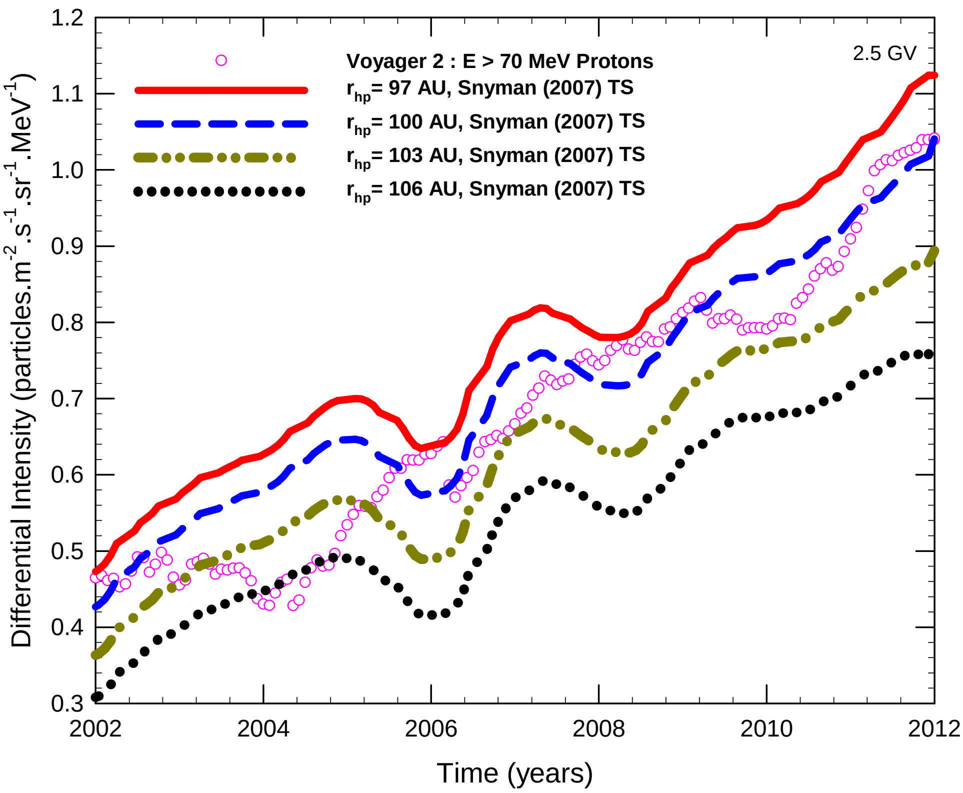

Figure 10.11: Computed 2.5 GV cosmic ray proton intensities along the Voyager 2 trajectory since 2002 are shown as a function of time for different assumed heliopause radii, r_{hp}, and with a time-dependent TS position, r_{ts}, proposed by *Snyman* (2007). Also shown are the $E > 70$ MeV proton observations from Voyager 2 (from `http://voyager.gsfc.nasa.gov`) as symbols (circles).

During the period 2002-2012, the position of the TS along the Voyager 1 as proposed by *Webber and Intriligator* (2011) oscillates between ∼96 AU to ∼80 AU. For the same period the heliopause is found to oscillate between 119 AU and 122 AU to compute compatible cosmic ray intensities (with 116 AU and 127 AU probably too extreme values). Not taking these extreme values into account, this shows that the excursions of the heliopause position is ∼3 AU (i.e. $r_{hp} = 119 \pm 3$ AU) and is smaller when compared to the excursions of TS position (i.e. $r_{ts} = 88 \pm 8$ AU), similar to as predicted by *Wang and Belcher* (1999). The heliopause should not move too much because this would require motion of tremendous volume of plasma, since the heliopause separates solar and interstellar materials.

Next the effect of a time-dependent TS position on cosmic ray intensities along the Voyager 2 trajectory is studied assuming an asymmetric heliosphere as discussed in Chapters 8 and 9.

10.5 Modelling results along the Voyager 2 trajectory

Figure 10.10 shows the computed 2.5 GV cosmic ray proton intensities along the Voyager 2 trajectory when a steady-state (static) TS and time-dependent TS positions, as proposed by

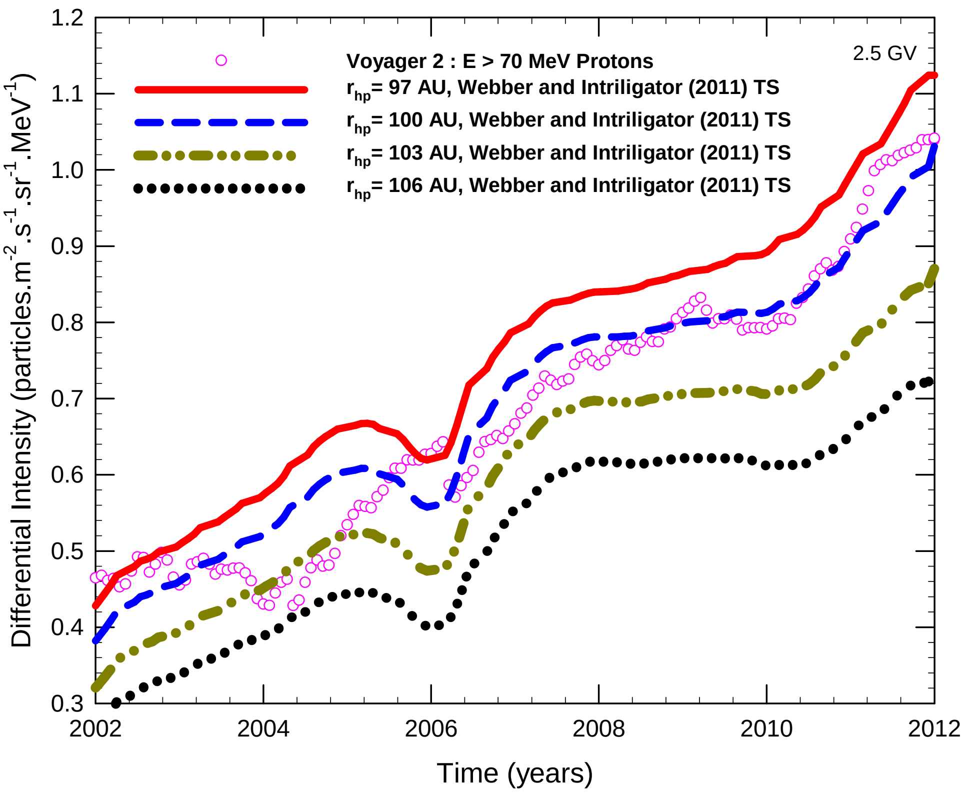

Figure 10.12: Similar to Figure 10.11 except that here modelling results are shown for a time-dependent TS position, r_{ts}, proposed by *Webber and Intriligator* (2011).

Snyman (2007) and *Webber and Intriligator* (2011), are assumed for a heliosphere with a modulation boundary (heliopause) at 100 AU. The computed results are compared to the $E > 70$ MeV proton observations from the Voyager 2 spacecraft (shown as circle symbols) for compatibility. From the figure it follows that the steady-state TS located at 80 AU (red solid line) follows the trends in the observations but fails to reproduce the detail for most of the time.

The computed cosmic ray intensities along the Voyager 2 trajectory using *Snyman* (2007) and *Webber and Intriligator* (2011) TS scenarios are also shown in the Figure 10.10 as blue dashed and black dotted lines respectively. From the figure it follows that the computed intensities for both scenarios are higher/lower and out of phase with the observations, similar to the scenario along the Voyager 1 trajectory as shown in Figure 10.6. Also, since both the proposed scenarios differ along the Voyager 2 trajectory the corresponding computed intensities also differ. The computed intensities using *Snyman* (2007) TS were fitting the observations for the period ∼2002, ∼2006 and ∼2009. This scenario computed higher intensities than the observations for the period ∼2003-2005, ∼2007-2008 and ∼2009-2011 and lower intensities for the period ∼2005-2006 and ∼2008-2009. Although the general trend is fine, this scenario fails to reproduce the observations in detail.

Continuing with Figure 10.10, the scenario which used *Webber and Intriligator* (2011) TS (black dotted line) computed cosmic ray intensities that fit the observations during the period ∼2003,

~2006 and ~2009-2011, but computed higher intensities than the observations during the period ~2003-2005 and ~2006-2009 and lower intensities during the period ~2002-2003, ~2005-2006 and ~2011-2012. Both scenarios again show a prominent out of phase calculation during the period ~2003-2005 when compared to observations. As argued above, a reason behind the failure to fit the observations with a model that uses a time-dependent TS could be the assumption of a static heliopause position.

Figure 10.11 shows the computed cosmic ray intensities along the Voyager 2 trajectory when a time-dependent TS as proposed by *Snyman* (2007) is used assuming different heliopause distances, namely 97 AU, 100 AU, 103 AU and 106 AU respectively. From the figure, it follows that a 97 AU heliopause (red solid line) scenario gives the general trend in the data but fits the observations only during the periods around ~2002, ~2006 and ~2008 when the TS was located at ~82 AU, ~81 AU and ~79 AU respectively. This scenario is probably too extreme. A 100 AU heliopause scenario (blue dashed line) fits the observations during the period ~2002-2003 when the TS moves from ~82 to ~86 AU. Also this scenario fits the observations during the period ~2009 when the TS was located at ~82 AU and during the period ~2012 when the TS was at ~79 AU. The yellow dash-dotted line representing a 103 AU heliopause is found to fit the observations during periods ~2003, ~2005 and ~2007 when the TS is at ~86 AU. The fourth scenario (black dotted line) fits the observations during the period ~2004-2005 when the TS is around ~90 AU and could also be considered as an extreme case. If indeed the heliopause position is dynamically changing and could be introduced as an additional solar cycle dependent parameter, then it is found that the heliopause is moving outwards from 97 AU to 106 AU in ~2 years during the period ~2002-2004 while the heliopause is found moving inwards from 106 AU to 97 AU during the period ~2005-2006 in ~1 year.

The computed cosmic ray intensities along the Voyager 2 trajectory using the *Webber and Intriligator* (2011) TS and with different assumed heliopause locations are shown in Figure 10.12. The 97 AU heliopause (red solid line) fits the observations during the period ~2002-2003 and ~2006 when the TS is near 80 AU and is again probably an extreme scenario. The heliopause at 100 AU scenario (blue dashed line) fits the observations during the periods ~2003, ~2008-2011 and ~2012 when the TS is located at ~81 AU, ~74-84 AU and ~76 AU. While the 103 AU heliopause scenario fits the observations during the period ~2004-2005 when the TS is located near 87 AU and the 107 AU scenario is compatible to observations at ~2004.5 when the TS is located at ~89 AU and can also be considered as too extreme. Again it is evident that the heliopause moves outwards with respect to the Sun from 97 AU to 106 AU during the period ~2002-2005 in ~3 years but takes only ~1 year to move inwards from 106 AU to 97 AU during the period ~2005-2006. When not considering the extreme values, the excursions of the heliopause position (100 ± 3 AU) when compared to the TS position (81 ± 7 AU) along the Voyager 2 trajectory is also found to be smaller, similar to the computed result along the Voyager 1 trajectory.

It follows that, the results along the Voyager 1 and Voyager 2 trajectories show that in order to reproduce cosmic ray proton intensities along both the spacecraft in detail, a time-dependent TS position along with a time-dependent heliopause position could be required in the model. Also it is found that the effect of a time-dependent TS position on cosmic ray intensities along the Voyager 1 trajectory is negligible during the period ∼2011-2012 when the spacecraft is close to the heliopause. However, during the same period a significant effect due to a time-dependent TS position is computed along the Voyager 2 trajectory because of the larger distance towards the heliopause for this spacecraft compared to Voyager 1.

10.6 The relationship between the heliopause and termination shock distances

The studies by *Muller et al.* (2006, 2009) computed the ratio between the heliocentric distance of the heliopause (r_{hp}) to that of the TS (r_{ts}) to be a constant, ∼1.4, in time (i.e. $r_{hp} = (1.40 \pm 0.03)r_{ts}$). Also work done by *Webber and Intriligator* (2011) showed that the ratio of the heliopause to TS distance along the Voyager 1 trajectory to be 1.5 ± 0.1 and along the Voyager 2 trajectory to be 1.35 ± 0.05. This section investigates this aspect from a cosmic ray perspective. Note that the ratio proposed by *Muller et al.* (2006, 2009) and *Webber and Intriligator* (2011) may change over a solar cycle.

Figure 10.13 shows the time-dependent TS position proposed by *Snyman* (2007) along the Voyager 1 trajectory as solid red line. The black dashed line represents the position of heliopause computed by multiplying the proposed TS position by 1.35. Note that the computed heliopause position in this work is not delayed by a year with respected to the TS position as assumed by *Webber and Intriligator* (2011). Also shown as symbols are the different heliopause distance scenarios which give compatible intensities with the Voyager 1 cosmic ray observations as shown in Figure 10.8 when the *Snyman* (2007) TS scenario is used in the model. Shown here is that these scenarios, deduced by comparing cosmic ray observations to model results, are compatible to the $r_{ts} \times 1.35$ line until 2010. Therefore indirectly confirming from a cosmic ray perspective that this ratio holds and that indeed a time-dependence in the heliopause position is needed when a time-dependence in the TS position is assumed, although the amplitude between solar minimum and maximum seems less.

However, after 2010 and until 2012, when the same ratio, 1.35, is assumed between the heliopause and TS position, then the resulting heliopause position moves inwards from ∼118 AU to ∼114 AU. Since Voyager 1 was already at ∼119 AU in January 2012 (see Figure 2.29) and not yet fully in the heliopause region until early 2012, the predicted position seems not correct after 2010. The TS position predicted by *Snyman* (2007) after 2010 needs to stay close to ∼88 AU in order to maintain the 1.35 ratio between heliopause and TS distance for the period 2010-2012 and to result in a heliopause at ∼119 AU. The shaded area in the figure represents this expected position of heliopause (∼119 AU) along the Voyager 1 trajectory during the period 2010-2012 for a time-dependent TS which stay close to ∼88 AU. This is also true from a

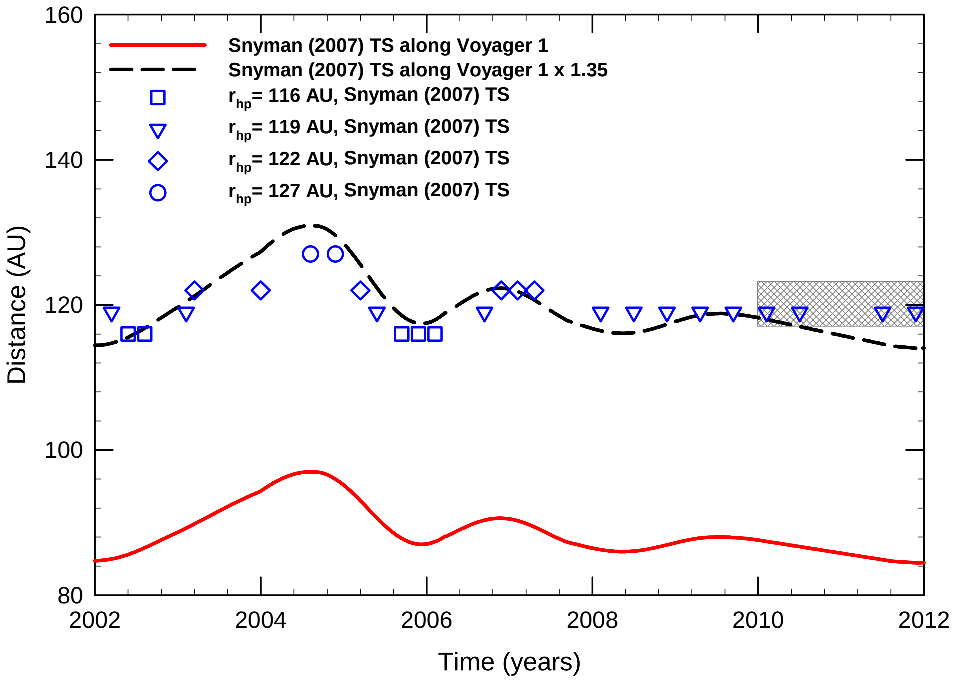

Figure 10.13: The time-dependent TS position, r_{ts}, (solid red line) along the Voyager 1 trajectory proposed by *Snyman* (2007) is shown along with the heliopause position, r_{hp}, (dashed black line) assuming that the ratio of the r_{hp} to r_{ts} remains constant at 1.35. The various symbols represent different r_{hp} scenarios predicted by the modulation model assuming a TS position as proposed by *Snyman* (2007). The shaded area represents the expected position of the heliopause along the Voyager 1 trajectory for the period 2010-2012.

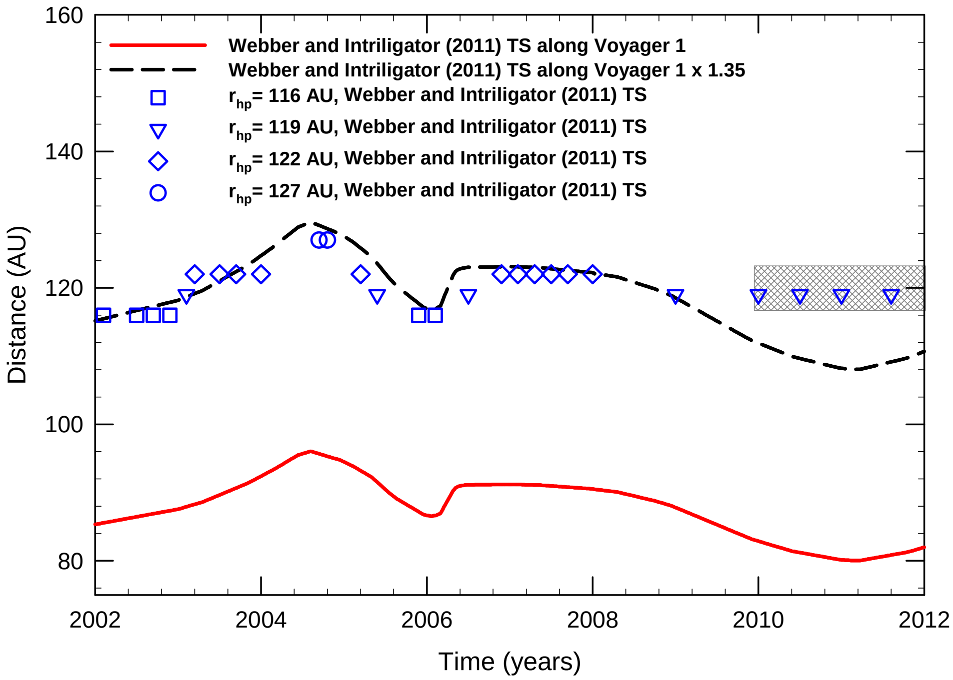

Figure 10.14: Similar to Figure 10.13 except that here the time-dependent TS positions as proposed by *Webber and Intriligator* (2011) is used.

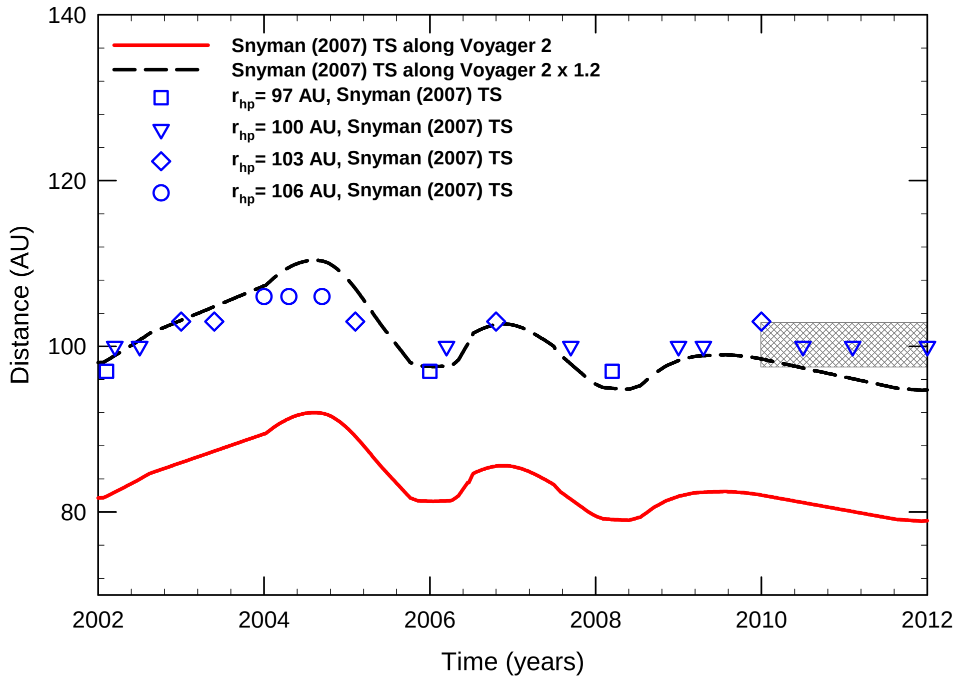

Figure 10.15: The time-dependent TS position, r_{ts}, (solid red line) along the Voyager 2 trajectory proposed by *Snyman* (2007) is shown along with the heliopause position, r_{hp}, (dashed black line) assuming that the ratio of the r_{hp} to r_{ts} remains constant at 1.2. The various symbols represent different r_{hp} scenarios predicted by the modulation model assuming a TS position as proposed by *Snyman* (2007). The shaded area represents the expected position of the heliopause along the Voyager 2 trajectory for the period 2010-2012.

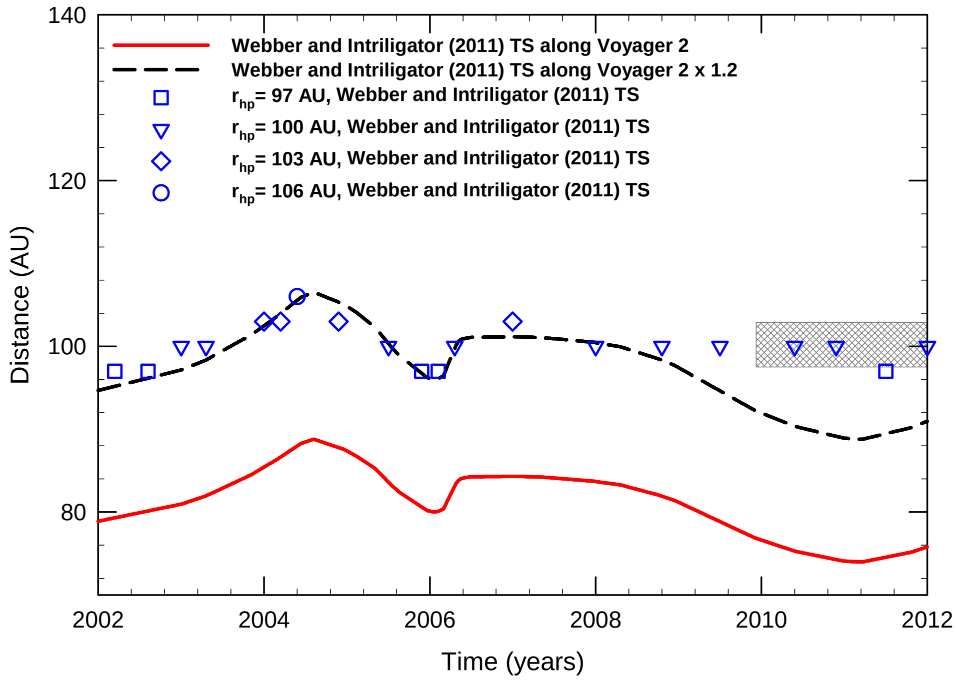

Figure 10.16: Similar to Figure 10.15 except that here the time-dependent TS position as proposed by *Webber and Intriligator* (2011) is used.

cosmic ray perspective where the model predicts a constant heliopause position as shown by the symbols to compute compatibility with the observations.

Similar conclusions follow for the TS scenario proposed by *Webber and Intriligator* (2011) which is shown in Figure 10.14. The figure shows the proposed TS and heliopause position using the 1.35 ratio. Again the different heliopause positions (shown as symbols), estimated by comparing cosmic ray model results to observations, largely fit the $r_{ts} \times 1.35$ line when the time profile of *Webber and Intriligator* (2011) is used. After 2010, the TS position predicted by *Webber and Intriligator* (2011) also leads to a heliopause position smaller than that as predicted from Voyager 1 cosmic ray observations if the ratio 1.35 is used. Again the cosmic ray observations and model predict a steady value of heliopause position up to 2012 and therefore a TS that stay close to ∼88 AU during this period.

Figures 10.15 and 10.16 show the TS and heliopause positions along the Voyager 2 trajectory as calculated from the *Snyman* (2007) and *Webber and Intriligator* (2011) TS profiles. Also shown as symbols are the r_{hp} predictions by comparing cosmic ray model results to observations as in Figures 10.13 and 10.14. From both figures, it follows that a $r_{hp}/r_{ts} = 1.2$ is needed to largely fit different heliopause scenarios as shown by the symbols up to ∼2010. After 2010 both the proposed TS profiles lead to a much smaller heliopause radius than the required values from a cosmic ray perspective. The heliopause position in 2012 computed using the 1.2 ratio and *Snyman* (2007) and *Webber and Intriligator* (2011) TS scenarios result in a heliopause position at ∼90 AU. Voyager 2 was at ∼97 AU in January 2012 (see Figure 2.29) and has not yet entered the heliopause region. This suggests that in order to maintain the 1.2 ratio the TS must be located close to ∼84 AU during the 2010-2012 period leading to a heliopause position of ∼100 AU. Also the results along both Voyager trajectories show that the ratio between r_{hp} to r_{ts} along the Voyager 2 trajectory is smaller when compared to the one along the Voyager 1 trajectory possibly due to a heliospheric asymmetry.

10.7 Summary and conclusions

In this chapter a time-dependent TS position was implemented in the model and time-dependent cosmic ray modulation along the Voyager 1 and Voyager 2 trajectories was computed. The TS positions as proposed by *Snyman* (2007) and *Webber and Intriligator* (2011) along both the Voyager trajectories were used as additional time-dependent input parameters in the model. The computed cosmic ray intensities along both the spacecraft were compared to the $E > 70$ MeV proton observations on-board both Voyagers. It was shown (in Figures 10.6-10.12) that implementing such a time-dependent TS profile alone in the model did not lead to improved compatibility with the observations (compared to that already shown in the previous chapters) and that a time-dependent TS position along with a time-dependent heliopause position is required. The excursions of heliopause position is found to be 119 ± 3 AU along the Voyager 1 trajectory and 100 ± 3 AU along the Voyager 2 trajectory. These heliopause excursions (∼3

AU) are found to be smaller compared to the excursions of TS positions (∼8 AU).

The study also suggests that the ratio between the heliopause distance and TS distance vary around some background constant value over a solar cycle. This aspect was proposed by *Muller et al.* (2006, 2009) and was tested using the *Snyman* (2007) and *Webber and Intriligator* (2011) TS profiles along both the Voyager trajectories. The different heliopause positions, indirectly estimated by comparing the cosmic ray model results to Voyager cosmic ray observations, are compatible until ∼2010 to the heliopause positions computed by multiplying the proposed TS positions by a constant (as shown in Figures 10.13-10.16). The average ratio of the heliopause to TS position along the Voyager 1 trajectory is found to be 1.35 and along the Voyager 2 trajectory it is found to be 1.2 until ∼2010. The smaller ratio along the Voyager 2 compared to the Voyager 1 is possibly due to a heliospheric asymmetry. After 2010, the heliopause position and TS position is found to be nearly a constant until 2012 which is different to that calculated from the proposed TS profiles from *Snyman* (2007) and *Webber and Intriligator* (2011) for these periods. The model predicts the heliopause and TS positions in 2012 at ∼119 AU and ∼88 AU along the Voyager 1 trajectory and ∼100 AU and ∼84 AU along the Voyager 2 trajectory.