Modelling the Influence of Corotating Interaction Regions on Jovian MeV-electrons

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Abstract. Corotating Interaction Regions (CIRs) are recurrent structures in the solar wind characterized by velocity jumps and a magnetic field compression. Since the 1970s it is known that Jupiter is a quasi-continuous source of MeV-electrons dominating the flux in the inner heliosphere. In connection with CIRs, this flux is modulated mainly by changing propagation conditions in the inner heliosphere. In order to model these recurrent variations in Jovian electron intensity the VLUGR3-Code was used to solve Parker’s Transport Equation. The diffusion as well as the solar wind speed are modelled from 0.1 to 50 AU. Two different approaches are used, one derived by Kissmann (2002) and another by Giacalone et al. (2002) which was further developed. The simulation results are compared to IMP-8 electron count rates to investigate the differences of the two solar wind models in the propagation code.

1. Introduction

Statistically significant 27-day variations are detected in spacecraft data of the galactic cosmic ray intensities, the electron count rates, the magnetic field and the solar wind speed data. Because these variations are all in phase, it is reasonable to assume a common cause. The most probable of the discussed causes are Corotating Interactions Regions (CIRs) which occur if a coronal hole extents into the ecliptic plane. As the high-speed solar wind originating from the coronal hole runs into a slower preceding solar wind as it is shown in Figure 1, a region of high magnetic flux and particle density is formed. According to [1] and [2] these CIRs are often recurrent structures if the extension of the coronal hole is stable over several solar rotations.

The compression of solar wind influences the heliospheric magnetic field and particle propagation conditions as described in section 2 according to [3, 4]. The two presented model setups by [5, 6] and [7] both vary the particle propagation as well as the magnetic connectivity via the solar wind speed and the variation of the diffusion inside a CIR inverse to the magnetic flux density.

The particle distribution is computed by using the VLUGR3-Code [8, 9] to solve Parker’s transport equation [10] on a grid with locally varying parameters.

Apart from that the model setups differ in calculating parameter changes caused by a CIR. The setup by [5, 6] decreases the diffusion coefficient inside a CIR independently from the solar wind speed. Based on [7] the second setup derives the variation of the diffusion tensor from the derivative of the solar wind speed.
Figure 1. Sketch of the magnetic field line configuration that leads to a CIR, taken from [11].

2. CIRs And Low-Energetic Electrons

2.1. The Structure of CIRs

CIRs are a direct consequence of Parker’s heliospheric magnetic field and were predicted to exist already by himself [4]. In Parker’s model the magnetic field lines are "frozen" into the solar wind and connect particles of the same source regions. Due to the Solar rotation with an angular velocity of $\Omega_S$ the longitudinal position changes with respect to the source region and the connecting magnetic field line is bent to an Archimedian Spiral (called Parker Spiral in this context) with a curvature depending on the radial solar wind speed $u$

$$\phi(r) = \phi_0 + \frac{\Omega_S \cdot \sin \Theta_0}{u}(r - R_S) \tag{1}$$

if the source region is defined by the longitudinal angle $\phi_0$ and the co-latitudinal angle $\Theta_0$ whereas the radial location of the source region is at the solar radius $R_S$ and the radial distance from the source surface is $r$.

Considering Eq. (1) higher solar wind speeds lead to lesser bending spiral magnetic field lines. As shown in Figure 1 the fast solar wind cannot overtake the slower one, because their corresponding Parker spirals cannot cross each other. Therefore they align and form a so-called stream interface ([12, 13]), a region of high magnetic and particle density. The area around the stream interface is also called compression region due to the increase of magnetic pressure and particle density and is associated with a rarefaction region located at the angle where the fast solar wind descends to smaller velocities again and the particle and magnetic densities are decreased.

The pressure gradient between the compression region and its surrounding area causes two pressure waves which expand into the fast and the slow solar wind regions and widen the CIR thereby decreasing the velocity gradient.

If the difference between the fast and the slow solar wind speed is higher than the propagation speed of the pressure waves in the plasma, they become shock waves, most of them at a radial distance of $2 - 3$ AU [14].

At even further heliocentric distances of $r = 5 - 8$ AU these structures can merge to so-called Merged
Figure 2. The Kissmann model for the solar wind speed. In the left plot over a full solar rotation at Earth’s orbit the shaded area indicates the width of the Compression Region, which is referred to as $\Delta \Phi_C$ in Eqs. (3) and (4). The beginning of the CIR is given by the angle $\phi_C$. The right plot shows the solar wind speed variation for radial distances between the Solar surface and 30 AU. The radial damping is modelled the function $d = \max((25 \text{ AU} - r)/r, 0)$ to smooth out the variation at distances larger than 25 AU.

Interaction Regions (MIRs). With increasing distance the shock waves weaken and CIRs/MIRs evolve to Corotating Pressure Enhancements (CPEs) as described by [14].

Due to the limitations of the used code shock waves and MIRs could not be considered in our CIR model and therefore don’t contribute to the modeling results.

2.2. Jovian Electron Transport
The VLUGR3 code, described in [8, 9], solves Parker’s Transport Equation numerically in three spatial dimensions and time. Due to this limitation in the number of dimensions it is not possible to calculate energy spectra. Therefore only 7 MeV Jovian electrons were used to investigate the modulation and propagation effects caused by the model CIRs.

Jupiter is known as a source of low MeV electrons since the Pioneer 10 flyby in 1977 (c.f. [16], [17] and [18]) and can even be considered as point-like on larger scales according to [19], [20] and [21]. Due to Jupiter’s synodic period of 13 months which determines the magnetic connectivity between the Earth and Jupiter a long-term variation of this period is detected in the electron count rates. Despite this 13 months period also the shape of the Jovian spectrum is well investigated and found to dominate the global spectrum in its low MeV range up to $\approx 20$ MeV within the inner heliosphere for distances $r \leq 20 – 30$ AU by [22].
The described approach has already been used successfully by [6], [11] and [23] for numerical parameter studies as well as for comparison with electron spacecraft data. The VLUGR3 code computes the differential electron intensities \( j = P^2 \cdot f(\vec{r}, P, t) \), via solving the distribution function \( f(\vec{r}, P, t) \) given by Parker’s Transport Equation [10]

\[
\frac{\partial f}{\partial t} = \nabla \cdot (\hat{k} \cdot \nabla f) - \vec{u} \cdot \nabla f + \frac{1}{3} (\nabla \cdot \vec{u}) \frac{\partial f}{\partial \ln P} + S
\]

which takes the effects into account caused by diffusion (first term) via the diffusion tensor \( \hat{k} \) [24] as well as the convection of the particles via the solar wind speed \( \vec{u} \) (second term on the right-hand side). The third term represents adiabatic energy changes, while with \( S \) additional sources as Jupiter are included. Some of these terms depend on the rigidity \( P = pc/qg \) with the momentum \( p \), the speed of light \( c \) and the particle charge \( q \). Further dependencies involved are the position \( \vec{r} \) and the time \( t \).

In order to avoid any influence of boundary conditions on our simulation results in the inner Heliosphere’s ecliptic plane, the differential electron intensities were simulated form \( r_{min} = 0.01 \text{ AU} \) up to \( r_{max} = 50 \text{ AU} \) and over the whole latitudinal as well as longitudinal range.

### 3. Two CIR Models

#### 3.1. The Kissmann Model

The first model being implemented was the approach by [5, 6]. In this setup the longitudinal solar wind speed variation is defined by a sharp increase at the angle \( \phi_C(r) \), the width of that region and therefore the slope of the increase is determined by \( \Delta \phi_C \) as shown in Figure 2. Characteristic for the setup is a much softer decrease which stretches over the rest of the longitudinal range. The variation of \( \phi_C(r) \) with radius via a Parker spiral, leads to the radial profile of the solar wind speed that is also shown in Figure 2. To adjust the different velocities in the outer heliosphere a linear radial damping function \( d = \max((25 \text{ AU} - r)/r, 0) \) is applied, to let the CIR decline.

Technically this solar wind speed profile over \( \phi \) is realised by two equations: the sharp increase inside the CIR is described by

\[
u(r, \phi) = u_{\text{slow}}(1 + d \cdot f_{\text{var}} \cdot (1 + \cos(\pi \frac{\phi - \phi_C}{\Delta \phi_C})))
\]

while the long decrease outside the structure is determined by

\[
u(r, \phi) = u_{\text{slow}}(1 + d \cdot f_{\text{var}} \cdot (1 - \cos(\pi \frac{\phi - \phi_C}{2\pi - \Delta \phi_C}))),
\]

where \( f_{\text{var}} \) defines the amplitude of the variation inside the CIR, while \( u_{\text{slow}} \) is the velocity of slow solar wind at the source latitude.

The magnetic properties of the CIR are not directly taken into account but by their effect to Parker’s Transport Equation, precisely by the variation of the diffusion tensor \( \hat{k} \). The approach that \( \hat{k} \propto 1/B \) by [22] leads in the most simple way to a box-like decrease of the diffusion, and the high magnetic flux density region can be assumed as a diffusion barrier. Inspired by data, [6] uses a smoother decrease symmetric around \( \phi_C \) as shown in Figure 3.

This variation is implemented as a modulation factor to the standard value of \( \kappa_{||} \) with the parameter \( A = 1 - B_0/B_{\text{CIR}} \) scaling the variation to the magnetic flux density variation outside \( (B_0) \) and inside \( (B_{CIR}) \) the CIR

\[
\kappa_{||/\text{CIR}} = \kappa_{||} \left( 1 - A \frac{1}{\cosh(\frac{\phi_C - \phi_C}{\Delta \phi_C})} \right)
\]

As the perpendicular component of the diffusion tensor is assumed to be proportional to the parallel one according to [22] and [25] it is changed in the same manner. Because the transport equation is
Figure 4. The Giacalone model for the solar wind speed. Similar to Figure 2 the left plot shows the solar wind speed variation over a full solar rotation at the earth orbit with $\phi_C$ as the beginning of the CIR and a shaded compression region. The right plot shows the radial development described by a similar damping function as for the Kissmann setup added to Eq. (6).

Figure 5. The Giacalone model for the parallel diffusion coefficient. The left plot shows the variation over a full rotation as in Figure 3 for the Kissmann setup but with the significant increase at the rarefaction region. The right plot showing the diffusion coefficient vs. the heliopheric distance differs from the corresponding plot due to this feature. The amplitude damping is linear for the Giacalone setup as it results from the derivative of the linear damped solar wind speed, cf. Eq. (7).

solved time-dependently with a rotating CIR, the diffusion barrier also shows an effect similar to the loss of magnetic connection between the Jovian source and an arbitrary point in space on the opposite side of the barrier.

As the following Giacalone Model in section 3.2, the Kissmann Model is limited to the latitudinal range of $3.5^\circ$ beneath and above the ecliptic plane where [22] showed the Jovian source to be most dominant. Likewise the limitation of one stream per rotation this range was choosen in order to keep the computational time short and could be extented for further investigations.

3.2. The Giacalone Model
To expand the possibilities of investigation a second solar wind speed and magnetic field model was implemented, based on the approach of [7]. The main difference to the first is, that it only parameterises the solar wind speed changes in the inner heliosphere and derives the magnetic field as a result of the velocity field.

For the solar wind speed variation the modified approach of [7] is used:

$$u(r, \phi) = u_{fast} + \frac{1}{2} \cdot (u_{fast} - u_{slow}) \cdot (\tanh \left( \frac{\phi_C - \phi - r \Omega_s/W}{\Delta \phi_C} \right) - \tanh \left( \frac{\phi_{RF} - \phi - r \Omega_s/W}{\Delta \phi_{RF}} \right)),$$

where $W$ is a constant speed which can be assumed as the speed with which the structure moves radially outward in the inertial reference frame. In Figure 6 the model is shown compared to spacecraft data of the simulated time period.
Figure 6. The Giacalone model’s solar wind speed and magnetic flux density in comparison to measurements. The data is taken from ftp://spdf.gsfc.nasa.gov/pub/data/omni/low_res_omni/

The Giacalone model additionally describes the rarefaction region and therefore includes also the fast solar wind speed $u_{fast}$ as measured inside the CIR, the angle at which the rarefaction region occurs $\phi_{RF}$ and also the angular width of the rarefaction region $\Delta \phi_{RF}$. Another difference to the model setup by [6] is that the CIR does not cover the whole longitudinal range which allows to vary its width.

In contrast to the original approach by [7], the corresponding magnetic flux density $B$ and therefore the diffusion coefficients are assumed to be antiproportional to the derivative of the solar wind speed $B(r, \phi) \propto \left| \frac{\partial}{\partial \phi} u(r, \phi) \right|$ based on the magnetohydrodynamic continuity equation.

The magnetic flux considered in the model seems to be in agreement with the corresponding data in Figure 6 and with the theoretical concept of CIR evolution because it reproduces the compression as well as the rarefaction region.

This allows to survey the influence of the rarefaction region on the Jovian electron modulation, if the simulated data for the Giacalone model are compared to the Kissmann model results.

4. Results and concluding remarks

The comparison of the IMP-8 daily electron data (gray) with the simulation results in Figure 7 shows, that the computed effects of the Giacalone model setup (red) seem to be in qualitatively good agreement with the observations. While the 13 month Jovian synodic period is already discussed by [6] we focused here on a period of good connection, as this is the period where we expect the greatest effects. The time period used in Figure 7 is one of absolute quiet time conditions, the interplanetary stream and sector structure has been discussed by [26]. Quantitatively the variations had to be intensified by the factor of 10 to be comparable to the results of the Kissmann setup (black).

For both models Figure 7 suggest that they reproduce the magnetic cutoff and its effect on the particle distribution in the surrounding quite reliably. The results of the Kissmann model show this as the wedge shaped intensity decreases every 27th day when the CIR is located between the spacecraft at Earth orbit and the Jovian source.

The different shape of the electron intensity variations in the Giacalone model shows the influence of the rarefaction region properties. The smoother influence of the 13 months period which is dominant in the Kissmann model can be understood via the increased diffusion coefficient in the rarefaction region which allows more efficient particle scattering and leads to a more uniform distribution.

Apart from that the influence of the increased diffusion is visible in the 27-day variation of the Giacalone model. Close to the compression region it appears to enable more particles to penetrate or cross the diffusion barrier what creates the smooth transition between the undisturbed electron flux and the decrease caused by the compression region and the magnetic cutoff.
Figure 7. Daily measured counting rates of the 2 – 12 MeV electron channel of IMP-8 (grey) plotted against the numerical solutions for the Kissmann model (black) and the Giacalone model (red). An offset is applied to the Giacalone results to allow for a better comparison of the three curves. Also the amplitude of the Giacalone results is intensified.

Both models allow for a quantitative treatment of major features in the velocity and magnetic field data as well as in the energetic electron counting rates. Minor features or finer details are reproduced qualitatively. Despite of their analytical simplicity the comparison of both models results allows to conclude that the influence of the rarefaction region’s properties on the Jovian electrons is not negligible and needs further investigations.

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