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High latitude Ulysses observations of CIR accelerated ions and electrons

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Abstract. From the comparison of the intensity maxima of ∼1 MeV/nuc. ions with those of the 40-65 keV electrons and higher energy ions (∼2-4 and 4-8 MeV/nuc.), during Ulysses' ascent to the solar south pole, 1992-1994, evidence has been found for the ∼1 MeV/nuc. ions observed at high latitude by the Ulysses spacecraft to have originated at mid-latitudes and greater radial distances. The key observations presented in this paper are; i) The ∼1 MeV/nuc. ion intensity maxima were observed to decay exponentially with latitude, above the streamer belt, whereas the electron intensity maxima and higher energy (∼ 4-8 MeV/nuc.) ion intensity maxima varied about a constant level, ii) When the ratios were taken of the ion intensity maxima to the electron intensity maxima for each of the CIR events, above the streamer belt, the ratios decayed exponentially with latitude, and iii) Upon the spacecraft's departure from the streamer belt, the electron maxima were observed to be delayed by ∼1-4 days, with respect to the ∼1 MeV/nuc. ion maxima. Within the streamer belt they had been typically simultaneous. Evidence was also found for a delay in the higher energy ($\gtrsim$2 MeV/nuc.) ions with respect to the lower energy ∼1 MeV/nuc. ions. From the exponential decay of the ion/electron ratios above the streamer belt, we concluded that the ∼1 MeV/nuc. ions originated from the CIR reverse shock at lower latitudes and greater radial distances, along with the electrons.

The observed delays in the electrons and higher energy ions were a consequence of the particles travelling from the distant reverse shock. Hence, it appears that the ions were accelerated at the reverse shock at lower latitudes, and not at the local poleward propagating reverse shocks as had been previously suggested.

Key words: acceleration of particles – interplanetary medium

1. Introduction

It has long been known that ions of energies ∼1 MeV can be accelerated in the heliosphere at the shocks which bound a CIR (Corotating Interaction Region), the interaction region between fast and slow solar wind streams. The ion intensity enhancements associated with CIRs in the ecliptic plane have previously been studied extensively (Barnes & Simpson 1976; McDonald et al. 1976; Christon & Simpson 1979; Christon, 1981; Tsurutani et al. 1982; Richardson et al. 1993; and references therein).

With the advent of the post-planet encounter phases of the Voyager 1 and 2, and Pioneer 10 and 11 missions, the latitude variations of the CIRs and their energetic ion populations were studied (Christon & Stone 1985; Gold et al. 1988; Decker et al. 1987). Christon and Stone found that the variations in the structure of the coronal hole at the Sun directly affected the evolution of the accelerated ion intensities at the spacecraft in the outer heliosphere, i.e., the latitudinal structure of the CIR was preserved out to the distances of the Voyager and Pioneer spacecraft. In terms of the overall latitudinal gradients for energetic ions (Gold et al. 1988; Decker et al. 1987), observations were only made over a limited latitudinal range (up to ∼30°), in the outer heliosphere, >20 AU, with only a weak latitudinal gradient of ∼-3 %/° being observed.

The Ulysses mission extends our range of knowledge of CIRs, and the related accelerated particles, up to high latitude ($\gtrsim$80°) in the inner (<5 AU) heliosphere. After the spacecraft's encounter with Jupiter in February 1992, it began its ascent towards the Sun's southern pole (maximum latitude occurring on day 256, 1994). As the spacecraft rose in latitude, it encountered a series of recurring enhancements in the solar wind speed (Bame et al. 1993), the first of which occurred about day 188 1992, and was followed by a series of solar wind speed enhancements, of up to ∼750 km s^{-1}, for subsequent solar rotations. This CIR was created by the interface between the fast solar wind from the polar coronal hole and the slower solar wind of the streamer belt. As the spacecraft rose above the streamer belt, $\gtrsim$29° south, the solar wind speed ceased decreasing to a minimum value of ∼400 km s^{-1}, as it had done previously. Once the spacecraft had reached ∼40° south the solar wind speed remained constant at ∼750 km s^{-1}. Despite the lack of a decrease in the solar wind speed observed at the spacecraft, reverse shocks from the CIR were observed to be present at the spacecraft at higher latitudes (Gosling et al. 1993; Balogh et

Send offprint requests to: G. M. Simnett al. 1995; Riley et al. 1996). Phillips et al. (1995), observed the reverse shock as high as 58° south on day 93 1994. The propagation of the reverse shocks to higher latitudes was viewed as a natural consequence of the tilted streamer belt in the model of Pizzo (1994). The energetic ions associated with the high latitude CIR have been discussed previously (Simnett et al. 1994, 1995; Sanderson et al. 1994; Simnett & Roelof 1995). Simnett et al. (1994) observed that there was a clear 26.0 day period in the recurrence of the energetic ion enhancements (Christon & Stone (1985) observed the same period for the recurrence of a CIR in the outer heliosphere during the previous solar cycle from a study of Pioneer and Voyager data). In addition to the 26.0 day period, there were also several phase shifts in the ion enhancement occurrences. These were attributed to a restructuring of the polar coronal hole. Recently, Roelof et al. (1997) have been able to associate variations of energetic ion and electron intensities, in the northern heliosphere, with variations observed in the structure of the northern polar coronal hole.

In Sect. 2.1, the variation of the ~1 MeV/nuc. ion intensity maxima were compared with the electron intensity maxima and ion intensity maxima at different energies. For the lower energy ~1 MeV/nuc. ions the intensity maxima decayed exponentially with increasing latitude, whereas for the highest energy (~4-8 MeV/nuc.) ion and electron intensity maxima, there was no decay. When the ~1 MeV/nuc. ion and electron intensity maxima were compared, the ratio of the two, for both protons and helium ions, was found to decay monotonically with latitude, despite large variations in the maximum values of the ions on an event-to-event basis. In Sect. 2.2, the time of the intensity maxima for both the electrons and higher energy ions were observed to be delayed with respect to the lower energy (~1 MeV/nuc.) ions.

In Sect. 3, these observations are discussed in the context of both the energetic ions and electrons observed above the streamer belt being accelerated at the more distant reverse shock, at lower latitudes. This is consistent with the interplanetary magnetic field model of Fisk (1996). In terms of the site of ion acceleration, this is contrary to what Simnett and Roelof (1995) suggested, where the ions were considered to have been accelerated locally at the reverse shock, which had propagated poleward, in accordance with the model of Pizzo (1994).

2. Observations

Observations were made predominantly with the HI-SCALE instrument on Ulysses. The HI-SCALE instrument can distinguish between different ion species using the CA 60 telescope, which has three silicon detectors (one of which acts as an anti-coincidence) and determines the species of ions from the values of dE vs. E. The electron intensities used in this paper were measured by the LEFS 150 (Low Energy Foil Spectrometer) telescope on HI-SCALE. The LEFS telescope consists of a thin foil, which prevents contamination of the electron channel by solar wind ions, with two 200μm silicon detectors, the second of which acts as an anti-coincidence. For a more detailed description of the HI-SCALE instrument see Lanzerotti et al. (1992).

Higher energy proton and helium ion data were also used from the LET on the COSPIN experiment. This telescope determines the species and energy of an ion using a double dE vs. E technique, with an array of four solid state detectors and a plastic scintillator casing which acts as an anti-coincidence. Ions are identified over the energy range ~1 to 75 MeV/nuc. For a more detailed description see Simpson et al. (1992).

2.1. Intensity variations with latitude

As the spacecraft climbed to increasingly higher latitudes, there was a series of enhancements in the magnitudes of the ion and electron intensities. These enhancements were associated with a CIR. In all, there were 27 CIR events observed clearly in the HI-SCALE ion data. The sidereal rotation rate of the equatorial photosphere is ~25.4 days, a value which is also applicable to the corona and coronal hole boundaries. Ulysses' right ascension was continually increasing slowly during this period, which resulted in the earlier observation of a 26.0 day period for the recurrence of the ion intensity enhancements for CIR events 2-21 (Simnett et al. 1994). Thus the data were divided into contiguous 26 day events. The first 26 day CIR event, which commenced on day 196 1992, was labelled "CIR 2" to be consistent with the numbering scheme established by Bame et al. (1993). To study the variation in the magnitudes of the ion and electron intensities during the spacecraft's ascent, the intensity maxima for the HI-SCALE 0.480-1.204 MeV protons, 0.39-1.28 MeV/nuc. helium ions and 40-65 keV electrons were determined by a 12 hour running mean procedure acting on hourly averaged data. The general observations associated with the intensity maxima have been discussed before (Simnett et al. 1994, 1995). When the ion and electron intensities for CIR 15 were examined in closer detail, there was a spurious solar flare particle feature observed. The maximum values displayed for CIR 15, in Fig. 1, were determined with this feature removed from the data.

Above the streamer belt, from CIR 10 onwards the ion intensity maxima decayed exponentially with latitude. By contrast, the electron intensity maxima appeared to vary about a constant level, with electron events being observed up to the highest latitudes of the spacecraft's southern polar pass. The general variation observed for the electron intensity maxima was of an order of magnitude. The geometric mean of the electron intensity maxima for CIR events 10-28 was 233 (all intensity values quoted are in units of particles/(cm^2 sr s MeV/nuc.)) as shown by a horizontal line on the electron intensity maxima in Fig. 1. When the electron intensity maxima of CIR events 10 to 28 were compared with that for CIR 2, the geometric mean value of the electrons (233) was found to be comparable with the maximum electron intensity value for CIR 2 (192). The proton and helium intensities, by contrast, appeared to be two to three orders of magnitude lower in the high latitude CIR events, i.e., CIR events 27-28, compared with the values for CIR 2.

The energy ranges over which the HI-SCALE protons and helium ions could be positively identified were limited. Therefore, in addition to the HI-SCALE data, the 12 hour running mean maxima for the 1.8-3.8 and 3.8-8.0 MeV protons and 1.7-

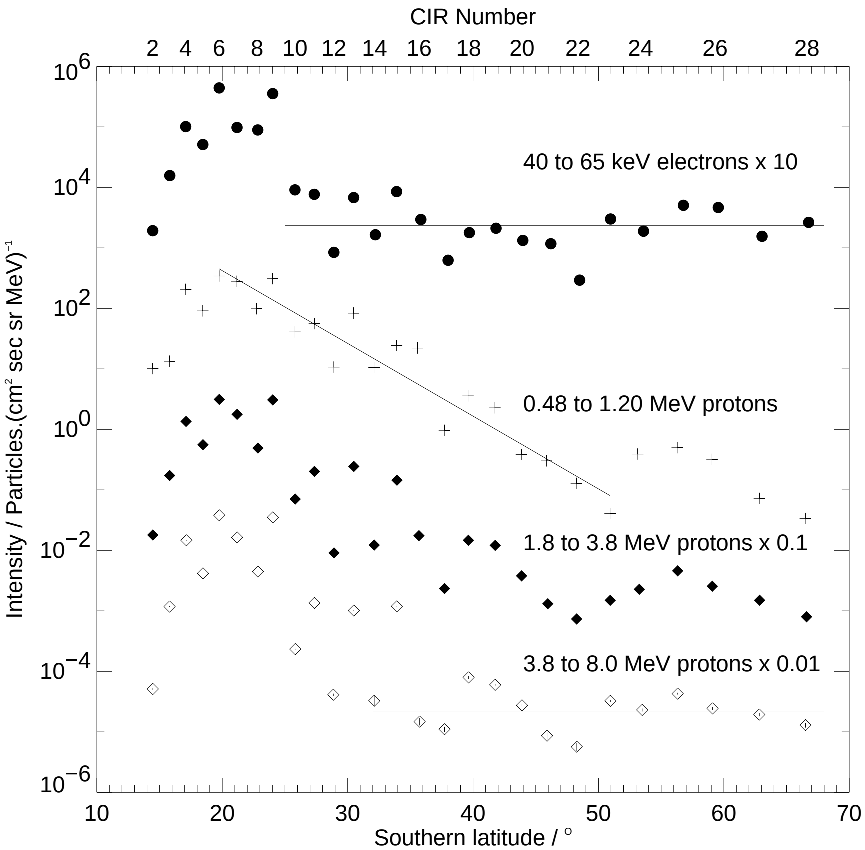

Fig. 1. Intensity maxima, as determined by 12 hour running mean maxima of hourly averaged data. The data plotted are 40-65 keV electrons $\times 10$ (filled circles), 0.48-1.20 MeV protons (+), 1.8-3.8 MeV protons $\times 0.1$ (filled diamonds) and 3.8-8.0 MeV protons $\times 0.01$ (open diamonds). The horizontal line passing through the electron maxima values corresponds to 10 x geometric mean value for CIR events 10 to 28, and the horizontal line passing through the 3.7-8.4 MeV proton maxima values corresponds to 0.01 x geometric mean value for CIR events 13 to 28 (excluding CIR 15). The straight line (least squares fit) through the 0.48-1.20 MeV proton flux maxima values represent the exponential decay with latitude (see text).

3.7 and 3.7-8.4 MeV/nuc. helium ions from the COSPIN LET experiment (COSPIN data courtesy of T. Sanderson) were examined with respect to the spacecraft's heliographic latitude. The proton intensity maxima at each of the three energy ranges and the HI-SCALE 40-65 keV electron intensity maxima are presented in Fig. 1. The helium ion intensity maxima are not displayed in this figure for reasons of clarity, but are qualitatively similar to the protons at a given energy range. At the higher of the two COSPIN energy ranges ($\sim$4-8 MeV/nuc.), the protons and helium ions for CIR 14 onwards[1] appeared to have dropped to a constant level, with geometric mean values for CIR events 14-28 (excluding CIR 15) of $2.3\text{x}10^{-3}$ and $1.3\text{x}10^{-4}$ respectively, as indicated by the horizontal line in Fig. 1 for the protons. This behaviour was more like that observed for the electrons than the ions at the lower HI-SCALE energy. The middle energy range ($\sim$2-4 MeV/nuc.) for both the protons and helium ions appeared to be a transition between what was observed at the lower and higher energy ranges.

The values of the ion intensity maxima ($\sim$1 MeV/nuc.) varied between individual passages of the CIR about the general trend which was observed. The variation appeared to be qualitatively similar to that of the electron maxima about their mean value. Therefore, this variation could represent changes in the CIR itself which accelerated the particles. Fig. 2 shows ratios of the proton and helium ion running mean maxima with respect to those of the electrons. In contrast to CIR events 2-11, where the proton/electron and helium/electron intensity maximum ratios showed a large amount of variation, the ratios appeared to show an exponential decay from CIR 12 onwards, i.e., when the spacecraft rose above the streamer belt (except for CIR 23, where the ion intensities at $\sim$1 MeV/nuc. were genuinely very low). This included CIR events 24 and 25, despite the fact that the ion intensity maxima for these events increased approximately by an order of magnitude compared with the CIR events which immediately preceded them. Fitting a straight line, with $\log_e$(ratio) as the ordinate and latitude as the abscissa, the latitudinal gradients obtained for the protons and helium ions were -17.5 %/° and -17.6 %/°, which correspond to an e-folding latitudinal distance of 5.7°.

2.2. Phase differences for the electrons and higher energy ions with respect to the ∼1 MeV/nuc. ions

In addition to the magnitude of the maximum values of the particle intensities, the 12 hour running mean procedure can also give a reasonable estimate as to the times at which the spacecraft encountered the maximum intensities. For CIR 15, a reasonable value could not be determined for the times of the maxima, due to the data being deficient after a large, non-CIR feature was removed. CIR 23 contained very few ions, as indicated in Fig. 1 and Fig. 2. This made the determination of the maxima for the ion events difficult to establish using the

[1] CIR 15 had maximum values that were anomalously high. This could reflect a significant contribution to the ion intensities from a preceding solar event.

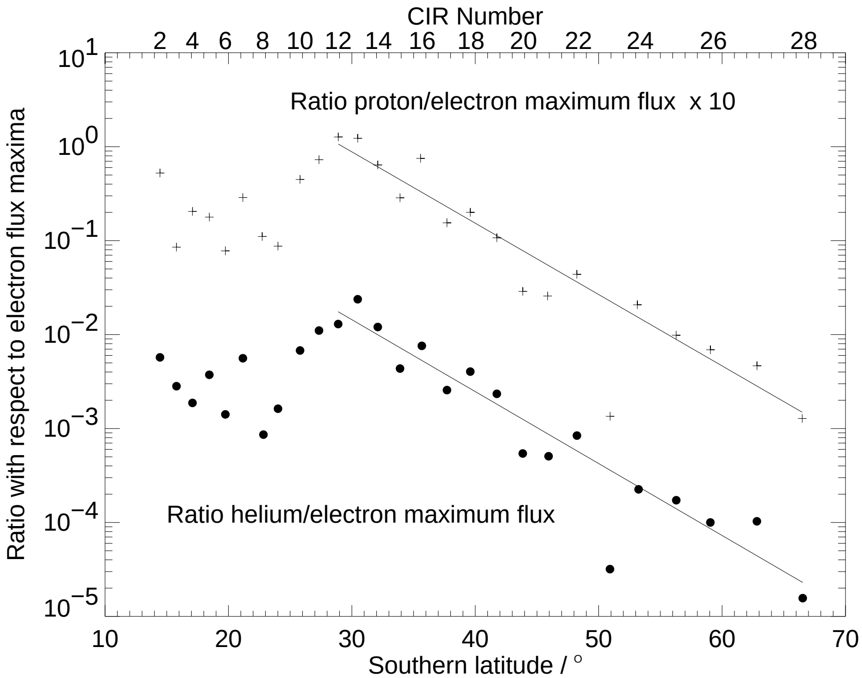

Fig. 2. Ratios of the 12 hour running mean maxima for $\sim$1 MeV/nuc. protons and helium ions with respect to the electrons. Original maxima values for the protons and electrons are shown in Fig. 1. The straight lines are least squares fits.

12 hour running mean results. However, the ion and electron intensity data had qualitatively similar intensity-time profiles, but shifted by $\sim 4\,^1/_2$ days. Therefore, the value for the electron delay of CIR event 23 was plotted in Fig. 3 as 108 hours.

When the times of the 12 hour running mean maxima were compared, the intensity maxima for the electrons and $\sim$1 MeV/nuc. ions, up to and including CIR 13, were observed to be almost simultaneous. However, as the spacecraft passed above the streamer belt there were delays apparent in the electron intensity maxima, compared with the ions, of the order of 1-4 days, with a mean delay of 64$\pm$8 hours (CIR 15 not included). This is shown in Fig. 3. From the figure there appeared to be a trend for the magnitude of the delay to increase with latitude, ignoring the values for CIR events 27 and 28.

When the times of the running mean maxima for the ions at the different energies were compared, there was found to be a definite delay in the higher energy ions when compared with the lower energy ions. For the events observed within the streamer belt, i.e., CIRs 2-12, when the times of the intensity maxima for the COSPIN ions were compared with the lower energy HI-SCALE ions, there appeared to be a general delay in the higher energy ions of $\sim$1-3 hours. Fig. 4 demonstrates this well for the helium ions at 0.39-1.28 and 1.7-3.7 MeV/nuc. When comparing the two higher energy COSPIN ranges, for both the protons and helium ions of CIRs 2-12, there was less variation, with over half of the events having maxima that were simultaneous at both energies. For CIR 13 onwards the delay observed for the higher energy ions increased. When the COSPIN data and the HI-SCALE data were compared, the delay in the higher energy helium ions (Fig. 4) appeared to increase to $\sim$10-100 hrs, at higher latitudes. This trend was similar to the delay which was observed for the electrons compared with the HI-SCALE ions. The delay for the 1.7-3.7 MeV/nuc. helium with respect to 0.39-1.28 MeV/nuc. helium can be seen in Fig. 4. In the case of the 3.7-8.4 MeV/nuc. helium ions, the delay could possibly be increased, in part, by the effects of anomalous cosmic ray (ACR) modulation. At this energy, ACR form a considerable portion of the observed helium ions, and hence their modulation by the CIR will result in in a decrease in the total ion intensities which are observed at the onset of the CIR ion event. As the modulation effect decreases as the CIR passes the spacecraft, the later CIR related ion intensities will be relatively enhanced, effecting an increase in the delay observed.

The 3.8-8.0 MeV proton maxima were also delayed above the the streamer belt, compared with the lowest energy proton maxima. The delay for the protons was typically $\sim$10 hours and was not as clear as that observed for the high energy helium ions. At the two COSPIN energy ranges, CIR events 12-16 had maxima which were simultaneous, to within $\pm$2 hours, especially for the protons, where 4 out of 5 were simultaneous. After CIR 18, for both the protons and helium ions, there was a delay for the highest energy ions compared with the $\sim$2-4 MeV/nuc. ions, as the spacecraft entered the near constant speed fast solar wind above 40° south. The delay which was observed with increasing energy can be explained if the the energetic ions were considered to have originated from a greater radial distance, as will be discussed further.

3. Discussion

The delay observed in the electrons, as also reported by Simnett et al. (1994), had previously been interpreted in terms of the electrons being accelerated at the distant reverse shock, beyond the spacecraft (Simnett & Roelof 1995). It was originally thought that this phenomenon could be explained purely in terms of the model described by Pizzo (1994). Pizzo's model proposed that

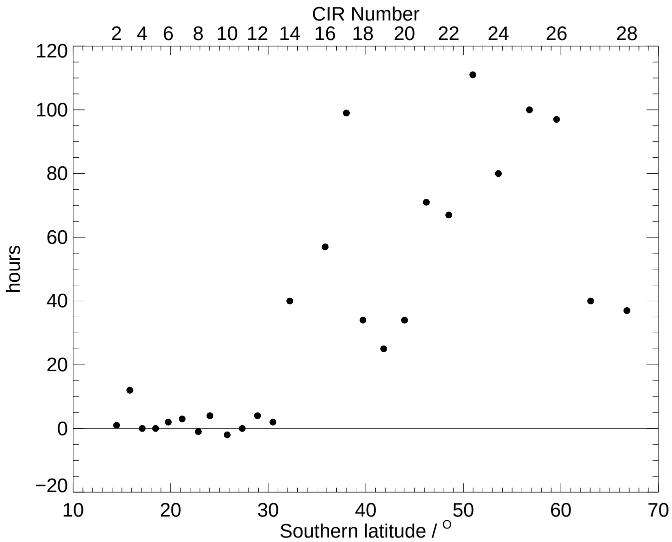

Fig. 3. The difference in time between the 12hr running mean maxima of the ∼1 MeV/nuc. ions and electrons (positive times correspond to ions arriving first). No value is plotted for CIR 15 as it was not possible to determine one reliably. The value for CIR 23 was determined by measuring the shift between the centroid at half the maximum values plotted in Fig. 1.

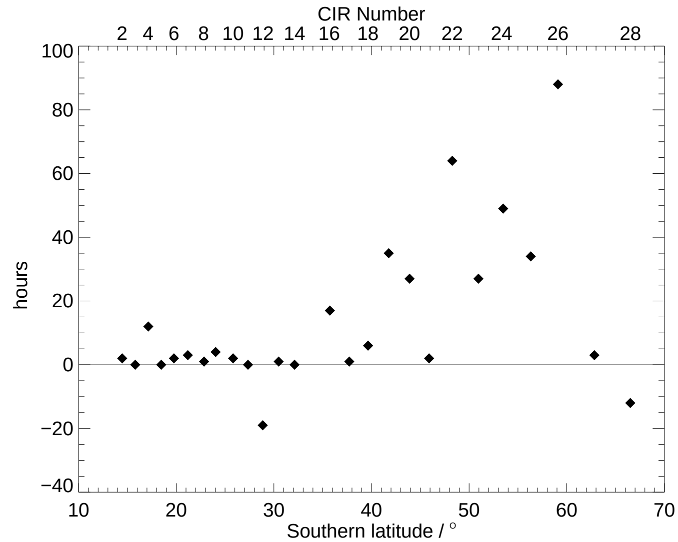

Fig. 4. Delay, in hours, between the 12 hour running mean maximum for 1.7-3.7 MeV/nuc. and 0.39-1.28 MeV/nuc. helium ions, with a positive difference equivalent to a delay in the 1.7-3.7 MeV/nuc. helium. No value is plotted for CIR 15 as it was not possible to determine one reliably. The value for CIR 23 was determined by measuring the shift between the centroid at half the maximum values plotted in Fig. 1.

due to the meridional shear forces which exist between the high latitude fast solar wind stream, from the polar coronal hole and the slower streamer belt solar wind, the shocks associated with the CIR would propagate predominantly meridionally and not azimuthally, as would be the case for a CIR in the ecliptic plane. This model was confirmed by the observations of the CIR reverse shock at Ulysses as far south as 58° (Phillips et al. 1995; Riley et al. 1996). It would have appeared therefore, that the reverse shock could have accelerated the ions directly at high latitudes.

There were, however, some problems with this model. Firstly, there were electron intensity enhancements observed regularly during the whole of the southern polar pass. Pizzo's model predicted that the maximum poleward motion of the reverse shock should be ∼17° (Riley et al. 1996). Since the tilt of the streamer belt was ∼30-40°, then the reverse shock could never propagate far enough south to explain the electron observations over the south pole. Secondly, the fact that ion intensity enhancements were observed at high latitudes, meant that they were not being accelerated locally at the spacecraft by the reverse shock. The reason being that the limit to the poleward propagation of the reverse shock was well below the latitudes where the ion enhancements were still observed. Also, after CIR 19 the reverse shock was not regularly encountered by the spacecraft.

Fisk (1996) proposed a model which could offer an explanation to the problems encountered with the suggestion of electron acceleration occurring at the distant reverse shock, and ion acceleration occurring at the local reverse shock. Fisk demonstrated that due to the tilt between the magnetic pole of the Sun and its heliographic pole, then as a magnetic field line is drawn out into the heliosphere by the solar wind, the footpoint of the field line will continuously increase and decrease in latitude as the Sun rotates. The consequence of this is that a magnetic field line encountering the spacecraft at high latitudes can exist at lower latitudes much further out in the heliosphere, with a possible difference in latitude of up to ∼30°.

If Fisk's model is considered, then the observed electron intensities, in addition to having originated at greater radial distances, could also have originated from lower latitudes. This would allow the electron intensity enhancements to be observed during the southern polar pass. The ions could equally have originated from lower latitudes also, in a similar fashion to the electrons. But how does this relate to the observations for the HI-SCALE ions, of both their attenuation with latitude and the fact that the electrons were delayed with respect to them?

In Fig. 2 the ratios of the ion intensity maximum to the electron intensity maximum, for both the protons and helium ions, were observed to decay steadily with latitude above the streamer belt. This decay was exponential despite the fact that the proton and helium ion intensity maxima were observed to vary on an event-to-event basis. Therefore, there must be an overall effect which was responsible for the relative ion maxima decrease, compared with the electrons, with the ions and electrons both originating from the same acceleration site.

The increase in the ion intensity maximum values for CIR 24 was coincident with a change in phase of the enhancements (Simnett et al. 1995). The change in phase would imply a restructuring of the coronal hole responsible for the CIR. The idea of a change in the CIR source at the Sun resulting in a change in the accelerated particle intensities was mentioned by Christon & Stone (1985) for Voyager and Pioneer data between 11 and 20 AU. Such restructuring and associated changes in the ion intensities were also observed in the outer heliosphere during mid-1993, by the Voyager spacecraft (Decker et al. 1995). Roelof et al. (1997) also made this conclusion for the CIR events encountered by Ulysses in the northern hemisphere.

The higher energy ions (especially ∼4-8 MeV/nuc.) appeared to propagate from the lower latitude reverse shock, in a similar manner to the electrons. This can be seen both in terms of the constant intensity maximum values above the streamer belt (Fig. 1) and the delay observed with respect to the HI-SCALE ions (Fig. 3 and Fig. 4). From the steady decay observed in the ion/electron maximum ratios (Fig. 2), then clearly the ions and electrons must share a similar acceleration site. Therefore the ∼0.5-1.0 MeV/nuc. ion attenuation with latitude, and the electron and higher energy ion delays must be a manifestation of the particles' propagation from their site of acceleration, which was at the distant reverse shock, at lower latitudes, and not locally at the poleward propagating reverse shock.

4. Summary

During Ulysses' ascent to the solar south pole in 1992-1994, a series of enhancements in the ion and electron intensities was observed. From HI-SCALE and COSPIN energetic particle data several important observations have been made. Firstly, the magnitude of the ∼1 MeV/nuc. ion increase was observed to decay exponentially with latitude above the streamer belt, whereas the electrons and higher energy ions varied about a constant level. Secondly, the ratio of ion/electron intensities was observed to decay exponentially with latitude. Thirdly, above the streamer belt, the electron intensity maxima were observed to be delayed with respect to the ∼1 MeV/nuc. ion maxima. A similar observation was made with regards to a delay in the higher energy ions with respect to the ∼1 MeV/nuc. ions.

From the steady decay of the ion/electron intensity maximum ratios, it was deduced that ion and electron intensities must have a common source and that a further mechanism was responsible for the ∼1 MeV/nuc. ion intensity maxima attenuation. In accordance with the interplanetary magnetic field model of Fisk (1996), the ions and electrons are both considered to have originated from the CIR reverse shock at a greater radial distance and lower latitude. Originally, it was suggested (Simnett & Roelof 1995) that only the electrons which were being accelerated at the distant reverse shock could be observed at the spacecraft at high latitudes, with the ions being accelerated locally. This was attributed to the observed delay between the two. In this paper, it has been suggested that both the ions and electrons observed above the streamer belt were accelerated at the lower latitude reverse shock beyond the spacecraft. The attenuation of the ∼1 MeV/nuc. ion intensities with latitude, though not the electrons, must be an effect due to their propagation.

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