Voyager observations of magnetic fields and cosmic rays in the heliosheath

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Received 6 June 2011; revised 6 August 2011; accepted 5 October 2011; published 17 December 2011.

[1] The major features of the profile of >70 MeV/nuc cosmic ray intensity (CRI) observed by Voyager 1 (V1) in the heliosheath from 2005.8–2010.24 are described by the empirical "CR-B" relation as the cumulative effect of variations of the magnetic field strength B. The CRI profile observed by Voyager 2 (V2) from 2008.60 to 2010.28 in the heliosheath is also described by the CR-B relation. On a smaller scale, of the order of a hundred days, a sequence of 3 CRI decreases observed by V1 during 2006 was interpreted as the effect of a propagating interplanetary shock first interacting with the termination shock, then moving past V1, and finally reflecting from the heliopause and propagating back to V1. Our observations show that the second CRI decrease in this sequence began during the passage of a "Global Merged Interaction Region" (GMIR), ~40 days after the arrival of the GMIR and its possible shock. The first and third CRI decreases in the sequence were associated with local enhancements of B. The magnetic field observations associated with the second sequence of 3 cosmic ray intensity decreases observed by V1 in 2007/2008 are more difficult to reconcile with the scenario of Webber et al. (2009) and the CR-B relation. The discrepancy might indicate the importance of latitudinal effects.

Citation: Burlaga, L. F., N. F. Ness, E. Stone, and F. B. McDonald (2011), Voyager observations of magnetic fields and cosmic rays in the heliosheath, *J. Geophys. Res.*, *116*, A12104, doi:10.1029/2011JA016914.

1. Introduction

[2] This paper compares observations of the magnetic field strength (B) and the cosmic ray intensity (CRI) by instruments on Voyager 1 (V1) and Voyager 2 (V2) when the spacecraft were approaching the termination shock (TS) and moving within the heliosheath. Section 2 describes the relationship between B(t) and the >70 MeV CRI(t) observed by V1 from 2004.0–2010.24. Section 3 describes the relationship between B(t) and CRI(t) observed by V2 from 2007.68–2010.28. The cosmic ray observations are from the PEN H channel of the Cosmic Ray Science experiment which measures primarily galactic cosmic rays >70 MeV, but it also includes a maximum 5%–10% background of ACR H >70 MeV. Since we consider only zeroth and first order effects, the ACR background is probably not very significant, and we shall simply speak of cosmic rays >70 MeV.

[3] A local relationship between the daily average of B(t) and the change in CRI(t) was observed in the Voyager data at 11 AU by *Burlaga et al.* [1985]. When B is strong (greater than the average magnetic field strength, $\langle B \rangle$ during an interval of the order of one year) the CRI decreases, and the rate of decrease of the CRI with time t is proportional to $(B/\langle B \rangle - 1)$. When B is weak ($\leq \langle B \rangle$), the CRI increases at a constant rate. Thus, local changes in the CRI(t) profile are related to the B(t) by the equations 1) $dCRI'/dt = -D \times (B/\langle B \rangle - 1)$ when $B > \langle B \rangle$, and 2) $dCRI'/dt = R$ when $B \leq \langle B \rangle$. The CR-B relation describes a threshold/relaxation process at a point, where CRI′ decreases when B increases above a threshold $\langle B \rangle$ and CRI′ recovers (relaxes back toward the initial state) when B is $< \langle B \rangle$. The CR-B relationship is an empirical relation, not a theoretical result.

[4] The CR-B relation explicitly includes $\langle B \rangle$ determined by the magnetic field observations, as well as the parameters D and R. Since these parameters can vary from year to year as a result of solar cycle variations and radial variations, it has been customary to analyze data in one year intervals, with D and R constant during each interval. The parameters D and R may be related to the diffusion coefficient and the effect of global drifts. The dependence of D on B and the fact that the diffusion coefficient depends on B suggest that D depends more strongly on diffusion than R does. Another parameter, C_o, enters when one integrates the CR-B relations. This parameter is the initial condition, determined by the cosmic ray intensity observed that the beginning of the interval that one chooses to describe by the CR-B relation.

[5] Given observations of the magnetic field B(t) during an interval of the order of one year, one can integrate the equations given by the CR-B relation to obtain a prediction for the cosmic ray intensity profile CRI′(t). Previous studies have

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0148-0227/11/2011JA016914

shown that with a suitable choice of D and R, CRI′(t) derived from the CR-B relation describes the basic features of the observed cosmic ray intensity profile CRI(t). The CRI(t) profile is strongly related to B(t), perhaps because the diffusion coefficient is inversely proportional to B or some power of B. At solar maximum, when there are many regions of strong magnetic fields associated with ejecta from the sun, the cumulative effect is a large sustained decrease in the CRI. During the declining phase of solar activity, when there are both enhancements and decreases in B associated with quasi-stationary flows from coronal holes as well as increases in B associated with transient ejecta, CRI(t) tends to fluctuate about a constant value. At solar minimum, when $\langle B \rangle$ is relatively small and $B/\langle B \rangle$ is not large (owing to the absence of many ejecta carrying strong magnetic fields from the Sun), the cumulative effect is an overall increase in the CRI.

[6] *Burlaga et al.* [2003] summarized earlier work and calculated the parameters D and R for the CR-B relationship observed by V1 and V2 in the supersonic solar wind for each year from 1983–2001 between 11 and 83 AU. The parameter D showed no systematic trend with increasing time, but on a semi-log scale it fluctuated about a most probable value ~0.004, ranging from ~0.0001–0.001. The parameter R decreased linearly with increasing time from ~0.003 in 1983 to ~0.0007 in 2001.

[7] Given the "universality" of the CR-B relation in the supersonic solar wind, it came as a surprise to find that a CR-B relationship did not describe the early observations of the heliosheath. *Burlaga et al.* [2005] found that strong magnetic fields (~0.1–0.2 nT) were observed by V1 from 2004 DOY 252 to 2005 DOY 115 in association with a relatively large increase in the CRI, in contrast to the decrease in intensity expected from the CR-B relation. Similarly, after crossing the TS for the last time on 2007 DOY 244 [*Burlaga et al.*, 2008], V2 observed both increasing CRI associated with strong B and decreasing CRI associated with weak magnetic fields to 2008 DOY 80, when V2 was moving through the heliosheath [*Burlaga et al.*, 2009a].

[8] These early observations of the absence of the behavior expected from the CR-B relation in the heliosheath were based on relatively small sets of data. It is possible that the CR-B relation was not observed because of the proximity of V1 and V2 to the termination shock. Now that we have a larger set of heliosheath data, it is of interest to re-examine the relationship between the CRI and B deeper in the heliosheath, where effects associated with the TS may be less important. That is one aim of this paper.

[9] *Webber et al.* [2007, 2009] noted a sequence of three decreases in the CRI in the heliosheath observations made by V1 during 2006 and another such sequence during 2007. They attributed the first decrease in each sequence to the interaction of a propagating shock wave with the TS, the second decrease to the arrival of the shock at V1, and the third decrease to the arrival of a shock after being reflected at the heliopause.

[10] The shock interactions that *Webber et al.* [2007, 2009] invoked to interpret their data were proposed and modeled for a pickup ion dominated medium by *Whang and Burlaga* [1994, 1995]. A shock driven by a "Global Merged Interaction Region" (GMIR, a region containing strong magnetic fields that moves past a spacecraft during an interval greater than one solar rotation) [*Burlaga et al.*, 1993] propagates through the distant heliosphere to the TS. The GMIR shock interacts with the TS, and a modified shock or a pressure pulse propagates through the heliosheath to the heliopause. Its interaction with the heliopause produces a transmitted shock that goes to the interstellar medium and a reflected shock or pressure pulse that moves back through the heliosheath toward the TS. Models of an interplanetary shock interacting with the TS and moving through the heliosheath were also presented by *Story and Zank* [1997] and *Washimi et al.* [2010]. *Luo et al.* [2011] and *Washimi et al.* [2011] modeled the event discussed by *Webber et al.* [2007, 2009]. *Luo et al.* [2011] modeled the cosmic ray propagation in detail, and showed clearly that a propagating interplanetary shock can produce at least two cosmic ray decreases in the heliosheath, 1) one CRI associated with the interaction of the interplanetary shock with the termination shock, and 2) another CRI associated with the propagating shock itself, as conjectured by Webber et al. The second aim of this paper, the subject of sections 4 and 5, is to examine the relationships between B(t) and the changes in the CRI(t) during the two sequences analyzed by *Webber et al.* [2007, 2009].

2. Large-Scale Voyager 1 Observations of B(t) and CRI(t) in the Heliosheath

[11] Daily averages of B(t) and CRI(t) measured by V1 in the heliosheath are shown in Figures 1a and 1b, respectively. The magnetic field data extend from 2004.00–2010.24, and the cosmic ray data extend from 2004.00–2010.50. The TS is evident by the large increase in B at 2004.97. The average B in the heliosheath from 2005.00–2010.24 was 0.10 nT; however, B fluctuates considerably, ranging from nearly 0 to more than 0.3 nT. The CRI increased after the TS crossing until 2005.79. Then the CRI fluctuated about ~1.1 between 2005.79 and ~2007.27. These fluctuations are discussed in more detail in section 3. Finally, from 2007.27–2010.24, the CRI increased nearly monotonically owing to the dominance of the term dCRI′(t)/dt = R corresponding to weak magnetic fields. The overall increase in the CRI is related to the recovery phase of the remarkable solar cycle 23 [*McDonald et al.*, 2010; *Mewaldt et al.*, 2010, and *Ahluwalia and Ygbuhay*, 2011], but there are small perturbations on this recovery curve associated with the large-scale fluctuations in the daily averages of B.

[12] For our analysis of the applicability of the CR-B relation in heliosheath, we consider the observations from 2005.79–2010.24, avoiding the region between the termination shock (at 2004.97) and 2005.79, where there are qualitative discrepancies between the observed CRI and that expected from the CR-B relation. The average B during this interval is $\langle B \rangle$ = 0.10 nT. We choose the initial value C_o = 1.09, determined by the observations, for integrating the CR-B relations. There are just two free parameters, D and R, which we determined by trial and error. With D = 0.0006 and R = 0.0007, and using the observed daily averages of B(t) in Figure 1a, integration of the CR-B relation gives CRI′, the solid red curve in Figure 1b. This curve describes the basic features of the observed CRI(t) profile from 2005.79–2010.24. The principal features of the observed CRI(t) profile (the plateau between 2005.79 and

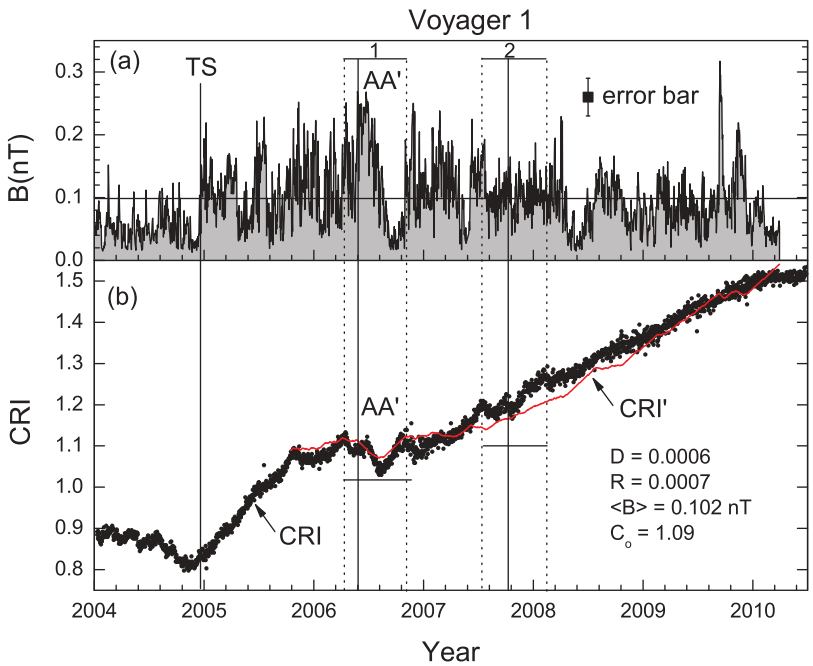

Figure 1. (a) Daily averages of the magnetic field strength observed in the heliosheath by Voyager 1 from 2004.0–2005.79. (b) Daily averages of the cosmic ray intensity >70 MeV/nuc observed by Voyager 1 (dots) and the cosmic ray intensity computed from the CR-B relation using the observed magnetic field strength in the parameters indicated (solid curve) from 2005.79–2010.24, avoiding the region between the termination shock at 2004.970 and 2005.79, where the CR-B relation does not hold. A notable feature in the CRI, designated AA′, is associated with an extraordinary enhancement and depression in B. The intervals one and two and associated vertical lines are periods discussed by *Webber et al.* [2009].

∼2007.27 and the monotonic increase from 2007.27–2010.24) and a notable feature, a large dip in the CRI in the middle of this plateau, are explained by the CR-B relation as the cumulative effect of the passage of the varying B(t) profile. In view of the large length of the interval being considered (4.45 years), the uncertainties in B (±0.03 nT), the sampling errors owing to the data gaps of ∼8 to ∼12 h each day, one concludes that the CR-B relation does apply in the heliosheath, sufficiently far from the TS.

[13] The parameter R for the fit shown in Figure 1b, R = 0.0007, is consistent with the value R = 0.0007 ± 0.0003 observed by *Burlaga et al.* [2003] in the solar wind during 2001. The parameter D = 0.0006 is within the range from ∼0.0001–0.001 found by *Burlaga et al.* [2003] from 1983–2001. The plateau between 2005.79 and ∼2007.27 is a result of the integrated effect of 1) decreases in the CRI associated with strong fields, 2) increases in the CRI associated with weak magnetic fields, and 3) magnetic fields near ⟨B⟩, which caused no change in the CRI. The nearly monotonic increase in the CRI from 2007.27–2010.24 is caused by the dominance of weak magnetic fields during this interval. These weak fields in the heliosheath are associated with the weak magnetic fields near the Sun and Earth approaching the minimum phase of solar cycle 23.

3. Large-Scale Voyager 2 Observations of B(t) and CRI(t) in the Heliosheath

[14] Daily averages of B and the CRI measured by V2 during a 2.6 year interval in the heliosheath are shown in Figures 2a and 2b, respectively. The magnetic field data and cosmic ray data extend from 2007.68 (just after the TS crossing at 2007.66) to 2010.28. The average B during this three year interval in the heliosheath is 0.10 nT, but it fluctuates considerably from nearly 0 nT to more than 0.3 nT. The variation of the CRI observed by V2 (Figure 2b) is very different than that observed by V1 (Figure 1b). Most notably, the large nearly monotonic increase in the CRI observed by V1 in the heliosheath from 2009.23–2010.28 was not observed by V2.

[15] Let us compare CRI(t) measured by V2 with CRI′(t) derived from the CR-B relation for the interval from 2008.6–2010.28. The average magnetic field strength in this interval, ⟨B⟩ = 0.1 nT, and the initial value of CRI, C_o = 1.195, are determined from the observations. The remaining two parameters in the CR-B relation, D and R, are determined by trial and error. The solid red curve in Figure 2b, CRI′, is computed from the CR-B relation using the magnetic field observations B(t) with the parameters D = 0.004 and R = 0.0008. The parameter D = 0.004 used to fit the observations is consistent with range of values found by *Burlaga et al.* [2003] from 1983–2001, and the corresponding parameter R = 0.0008 is consistent with the value R = 0.0007 ± 0.0003 observed by *Burlaga et al.* [2003] in the solar wind during 2001.

[16] The profile CRI′(t) derived from the CR-B relation shows the basic features observed by V2 in the 1.68 year interval from 2008.6–2010.28. The principal features of the CRI profile (the nearly monotonic increase from 2008.6–2009.24, the decrease from 2009.24–2009.39, the plateau

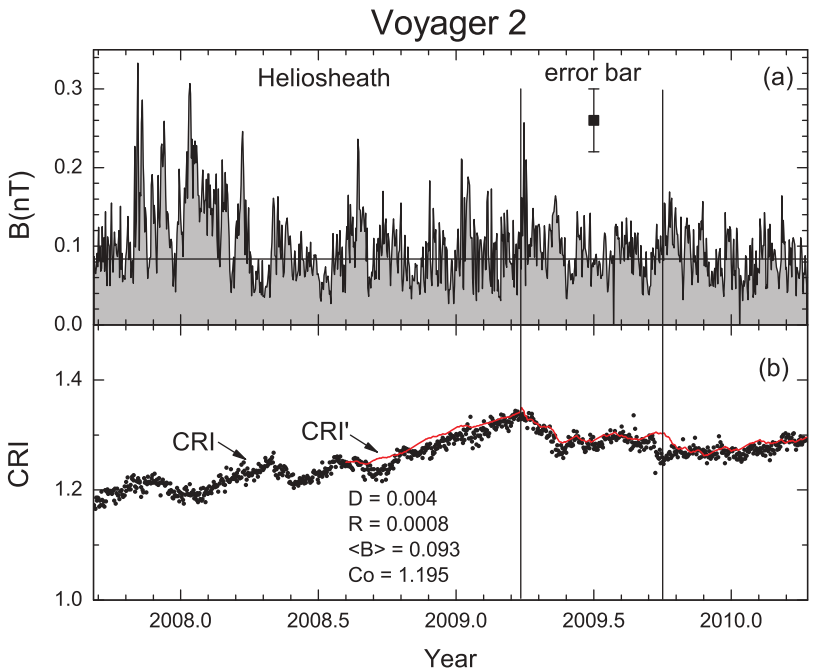

Figure 2. (a) Daily averages of the magnetic field strength observed in the heliosheath by Voyager 2. (b) Daily averages of the cosmic ray intensity >70 MeV/nuc observed by Voyager 2 (dots) and the cosmic ray intensity computed from the CR-B relation from 2008.6–2010.28 (solid curve) using the observed magnetic field strength and the parameters indicated. Data in the region from the termination shock at 2007.66–2007.68 are excluded from the fit because the CR-B relation does not fit the data in this region.

from 2009.38–2009.73, and the plateau from 2009.73–2010.28) are explained by the CR-B relation as integrated effects of the observed B(t). We conclude that the CR-B relation does apply to the V2 observations in the heliosheath, sufficiently far from the TS.

[17] Although there are moderate amplitude fluctuations of B during the interval 2008.6–2009.24, the CR-B relation with the observed B(t) predicts an increase in the cosmic ray intensity, consistent with the observations. The net effect of the weak magnetic fields during this interval dominates the tendency of the strong fields in the fluctuations to cause a decrease in the CRI. The passage of a region of magnetic fields stronger than average during an interval of several days (a "Merged Interaction Region," [*Burlaga et al.*, 1985, 1993, 2003]), beginning at 2009.24, caused a decrease in the CRI. The nearly constant CRI from 2009.38–2009.73 and from 2009.73–2010.28 is the cumulative effect of a series of enhancements and decreases in B(t). The small decrease in the CRI at ~2009.73 is related to the passage of a MIR. The small offset between the time of the decrease in CRI(t) and the time of the decrease in CRI′(t) shows a limitation in the CR-B relation, possibly associated with uncertainties in the measurements of B and sampling errors, or perhaps with energetic particle propagation effects.

4. A Sequence of Three Cosmic Ray Intensity Decreases Observed by V1 During 2006

[18] *Webber et al.* [2007, 2009] noted a sequence of three decreases in the CRI observed by V1 at 2006.29, 2006.57, and 2006.89. These decreases in the CRI are shown in Figure 1b. Webber et al. attributed the first decrease to the interaction of a propagating interplanetary shock with the TS, the second decrease to the arrival of the shock at V1, and the third decrease to the reflection of the shock from the heliopause back to V1. This hypothesis is very important, since Webber et al. used it to estimate the size of the heliosheath and the speed of disturbances in the heliosheath.

[19] *Webber et al.* [2007, 2009] suggested that a shock (observed by V2 near 79 AU in March, 2006) was responsible for the sequence of events described above. The presence of this propagating interplanetary shock was inferred by *Richardson et al.* [2006] from a jump in the speed, density, and temperature observed by V2 between days 59 and 60, 2006. The shock crossing occurred in a data gap, when V2 was not tracked by the Deep Space Network. Although the shock was not observed directly, it was probably present. The magnetic field strength did not increase across the data gap, hence across the shock. The CR-B relation implies that the observed decrease in the CRI was not produced by the shock itself.

[20] Consider the V2 observations of B(t) and CRI (t) during 2006 in more detail. Figure 3a shows the daily averages of B observed by V2, and Figure 3b shows the corresponding CRI(t) at V2. An increase in B by a factor of 2–4 was observed on DOY 61, a day or two after the presumed shock, and strong magnetic fields were observed from DOY 61–100.

[21] The solid red curve in Figure 3b shows CRI′ at V2 calculated from the CR-B relation using the observed B(t) shown in Figure 3a and the parameters C_o = 0.975, D = 0.006, and R = 0.002. The CR-B relation predicts a significant decrease in the CRI after passage of the shock,

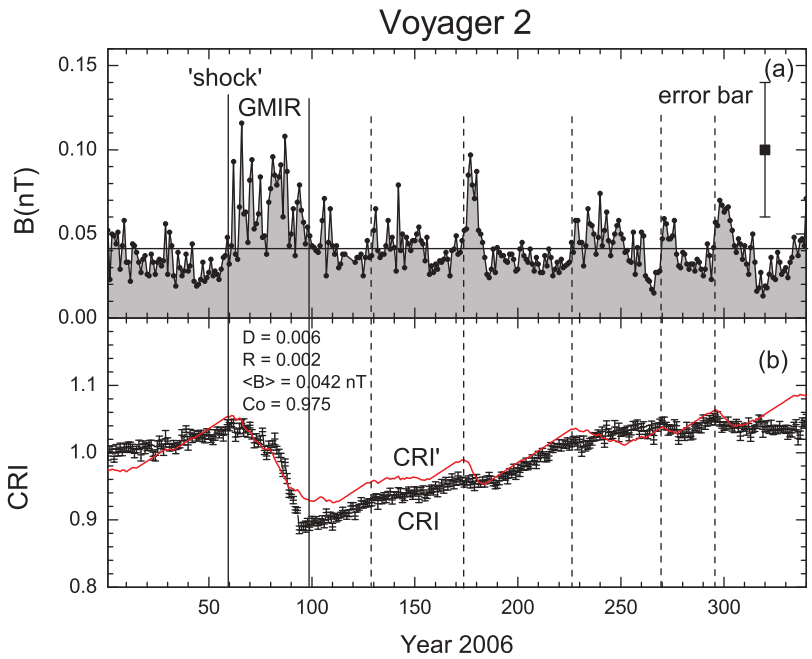

Figure 3. (a) Daily averages of the magnetic field strength observed by Voyager 2 in the supersonic solar wind during 2006. (b) Daily averages and error bars of the cosmic ray intensity observed by Voyager 2 in the supersonic solar wind during 2006 and the cosmic ray intensity computed from the CR-B relation (solid curve) using the observed magnetic field strength and the parameters indicated. The solid vertical lines at the termination shock and behind it indicate a GMIR, characterized by relatively long interval of strong magnetic fields. The dashed vertical lines indicate MIRs.

but the CRI decrease was not caused by the shock. Rather, the CRI decrease was caused by the passage of a region with strong magnetic fields during an interval greater than a solar rotation, a GMIR. GMIRs extend around the Sun near the equatorial plane, and they can have a large latitudinal extent [*Burlaga*, 1995]. Following the passage of the GMIR, the CRI observed by V2 increased from DOY 110 to DOY 365, 2006, as shown in Figure 3b. The curve CRI′ predicted by the CR-B relation is consistent with the basic features of the CRI observed by V2 throughout 2006, to first order. Thus, the CR-B relation applies to the supersonic solar wind out as far as 80 AU along the trajectory of V2.

[22] Let us return to the observations of the three CRI decreases and B(t) made by V1 during 2006, shown in Figure 4. The most notable feature in Figure 4a is AA′, the quasi-sinusoidal variation of B(t) that begins with strong magnetic fields at 2006.38 and ends with weak magnetic fields at 2006.83. This feature was discussed by *Burlaga et al.* [2009b], who noted that it is the largest magnetic feature observed in the heliosheath, with a passage time of half a year and B ranging from 0.27–0.02 nT. The part of this region containing very strong magnetic fields is a GMIR, which is probably the same GMIR observed by V2 (Figure 3a).

[23] The cosmic ray intensity profile CRI′ predicted at V1 from the CR-B relation with the measurements of B(t) and the parameters D = 0.0015 and R = 0.0009, is plotted as the solid red curve in Figure 4b. The CRI ‘profile resembles the CRI profile observed in the heliosheath by V1 during 2006, showing that the CR-B relation applies out to 105 AU as far as the basic features are concerned. However, there are some important differences in detail. Most notably, the CRI decrease beginning at 2006.40 occurs significantly later than that predicted from the observed B(t) by the CR-B relation. In addition, the CRI increases from 2006.43–2006.49 despite the very strong magnetic fields, which is qualitatively inconsistent with the CR-B relation.

[24] The beginning of the first CRI decrease at 2006.29 in the sequence identified by *Webber et al.* [2007, 2009] is associated with an increase in B, as one expects if the CRI decrease were a local effect produced by the magnetic field. A nonlocal effect, such as the interaction of a shock with the TS, need not be invoked to explain the presence of the decrease, but it might explain why the observed decrease is smaller than that found from the CR-B relation.

[25] The third decrease in the CRI observed by V1 at 2006.89 (or perhaps somewhat earlier) is associated with an enhancement of B (Figure 4). We cannot determine whether or not this enhancement represents a pressure pulse reflected from the heliopause. The depth of the CRI decrease predicted by the CR-B relation is consistent with that observed within the uncertainties.

[26] According to the hypothesis of *Webber et al.* [2009], the onset of the second CRI decrease at V1 at 2006.49 should coincide with arrival of a shock at V1. Instead, the second CRI decrease occurred in the midst of the passage of a GMIR (Figure 4a), probably the same GMIR observed by V2. The CRI decrease began ∼40 days after the arrival of the GMIR and the pressure pulse or shock associated with the increase in B at the beginning of the GMIR. The scenario

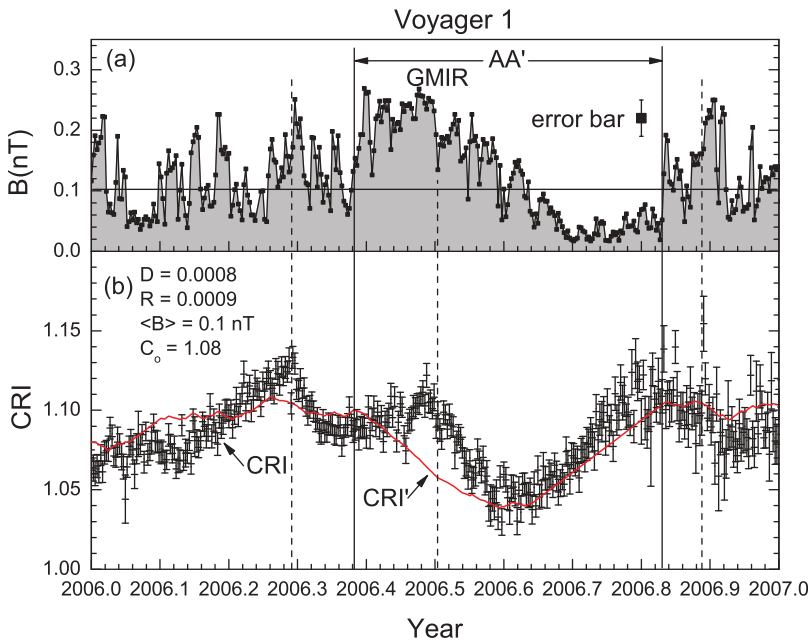

Figure 4. (a) Daily averages of the magnetic field strength observed by Voyager 1 in the heliosheath during 2006. (b) Daily averages and error bars of the cosmic ray intensity observed by Voyager 1 in the heliosheath during 2006 and the cosmic ray intensity computed from the CR-B relation (solid curve) using the observed magnetic field strength and the parameters indicated. The solid vertical lines show the boundaries of the region AA′ in Figure 1, which contains an extraordinary magnetic field strength profile related to a GMIR and a "rarefaction region" behind it. The first dashed vertical line marks the beginning of the decrease in CRI, showing that the decrease does not begin with the arrival of the GMIR. The second dashed vertical line marks the arrival of a MIR that produces a small decrease in the CRI.

proposed by *Webber et al.* [2007, 2009] should be modified to explain the relationship between the CRI and the magnetic field observations at V1, particularly the important effects of B(t) in the GMIR.

[27] The CR-B relation predicts that the GMIR should produce a symmetrical depression in the CRI profile, starting at the arrival of the GMIR, reaching minimum at approximately 2006.6 and recovering to its initial value at 2006.83, as shown in Figure 4b. The recovery profile CRI(t) observed by V1 is consistent with that determined from the observed B(t) by the CR-B relation. Why then did the decrease in CRI′(t) profile occur earlier than the decrease in the observed CRI(t) profile? *Washimi et al.* [2011] calculated that a pressure pulse should arrive at the time the GMIR was first observed by V1. They suggest that the delay between the CRI decrease and the arrival of the pressure pulse "is probably due to diffusive character of energetic particles and possible precursor associated with magnetosonic pulse." *Luo et al.* [2011] give a detailed calculation of the particle diffusion properties, but they model the GMIR as a shock, and do not show how the CRI decrease is related to the observed B(t) associated with the GMIR.

5. A Sequence of Cosmic Ray Intensity Decreases Observed by V1 During 2007/2008

[28] *Webber et al.* [2009] identified a second sequence of three CRI decreases in the V1 observations at 2007.56 ± 0.02, 2007.78 ± 0.02, and 2008.11 ± 0.03 (see Figure 1). As in the first sequence, they attributed the first decrease to the interaction of the propagating interplanetary shock with the TS, the second decrease to the arrival of the shock at V1, and the third decrease to the interaction of the shock with the heliopause.

[29] They associated the shock itself with the CRI decrease observed by V2 at 2007.43. This CRI decrease at V2 is shown in Figure 5b. As noted by *Webber et al.* [2009], a second CRI decrease was observed by V2 at 2007.49, which is also shown in Figure 5b. The two CRI decreases observed by V2 are associated with merged interaction regions, labeled MIR-1 and MIR-2, respectively, in Figure 5a. Both MIRs are relatively narrow compared to the GMIR observed by V2 in 2006. It is not clear that these two MIRS could have extended from V2 to V1. Neither of these MIRs was associated with a shock.

[30] The CRI′ profile observed by V2 in the supersonic solar wind during 2007, shown by the solid red curve in Figure 5b, was computed using CR-B relation with the magnetic field observations made by V2 just before it crossed the TS. This curve is based on the parameters $\langle B \rangle = 0.053$ nT and $C_o = 1.054$, which are determined from the observations, and the parameters D = 0.002 and R = 0.0012, chosen to give a best fit to the observed CRI profile. The CR-B relation describes the basic trend of the CRI profile observed by V2 during 2007 (Figure 5b). A nearly monotonic increase in the CRI′, consistent with the observations, is associated with the dominance of weak magnetic fields observed by V2 from DOY 1–148. This increase is followed by a plateau containing two CRI′

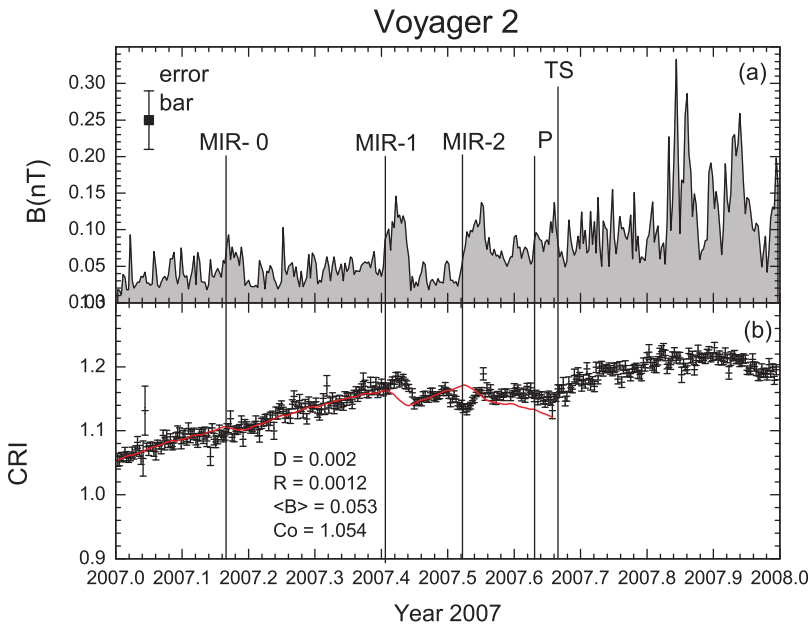

Figure 5. (a) Daily averages of the magnetic field strength observed by Voyager 2 in the supersonic solar wind and heliosheath during 2007. (b) Daily averages and error bars of the cosmic ray intensity observed by Voyager 2 in the supersonic solar wind and heliosheath during 2007, and the cosmic ray intensity computed from the CR-B relation in the supersonic solar wind (solid curve) calculated using the observed magnetic field strength and the parameters indicated. One vertical line indicates the position of the termination shock. The others mark the times of MIRs and an unusual enhancement of B ("P) just before the TS.

decreases associated with the two MIRs. Thus, the CR-B relation is valid to at least 84 AU along the trajectory of V2.

[31] The CRI′ profile observed by V1 in the heliosheath from 2007.42–2008.4 using the CR-B relation with the observed B(t) profile and the parameters C_o = 0.0006, R = 0.0007, and C_o = 1.2, is shown by the solid red curve in Figure 6b. Figure 6 shows the observed B(t) and CRI(t) on scales comparable to those in Figure 5. This CRI′ profile

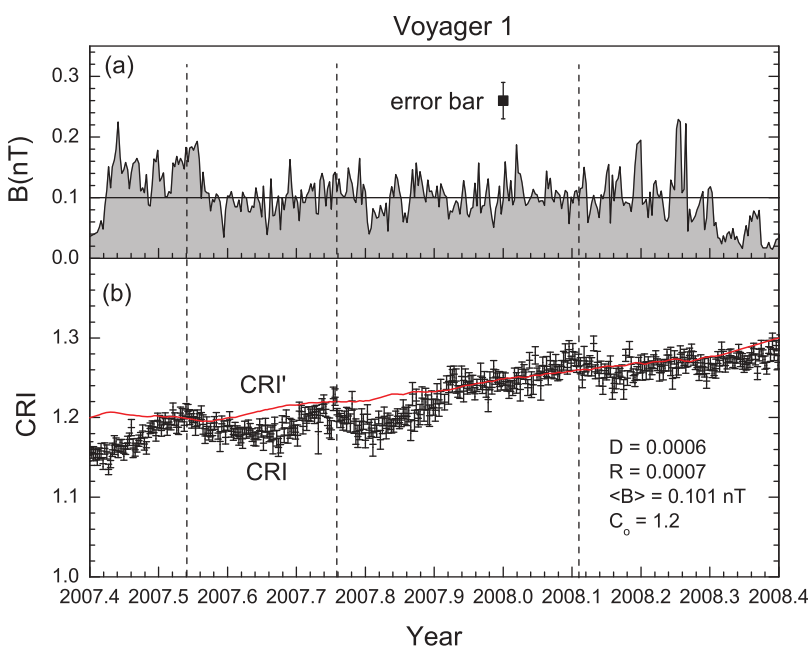

Figure 6. (a) Daily averages of the magnetic field strength observed by Voyager 1 in the heliosheath from 2007.4–2008.4. (b) Daily averages and error bars of the cosmic ray intensity observed by Voyager 1 in the heliosheath from 2007.4–2008.4, and the cosmic ray intensity computed from the CR-B relation (solid curve), calculated using the observed magnetic field strength and the parameters indicated. The vertical dashed lines mark the onset of CRI decreases.

follows the general trend of the CRI intensity, but it does not describe the first two CRI decreases that were observed by the CRS experiment. The magnetic field strength profile observed by V1 does not show the relatively strong magnetic fields required to explain the existence of the CRI decreases. Changing the parameters in the CR-B relation will not change this fact. The systematic and random errors in the observations give a 1σ uncertainty in each measurement of B of the order of $\pm$0.03 nT. These uncertainties, suitably distributed in time, could provide the enhancements and depressions in B needed to produce the CRI decreases, but this would require a curious coincidence.

[32] The times of the 3 CRI decreases identified by *Webber et al.* [2009] in the V1 data are indicated by the vertical lines in Figure 6. The third CRI decrease is very small, and it can be attributed to a few minor enhancements in B. The first CRI decrease at 2007.54 is associated with a significant enhancement in B at V1.

[33] The second CRI decrease observed by V1, beginning at 2007.76, was attributed by *Webber et al.* [2009] to the arrival of a shock related to MIR-1 at V2 at 2007.43. However, there is no significant enhancement in B in the V1 data that might be related to either a shock or a MIR. The absence of an enhancement in B also presents a problem in explaining the second CRI decrease that was observed. We conclude that the magnetic field observations associated with the second sequence of CRI decreases do not support the scenario of Webber et al., and it is not consistent with the CR-B relation even in its basic qualitative form.

[34] *Burlaga et al.* [2009b, Figure 1] showed that V1 was in a unipolar region during the interval from 2007.42 to 2008.4 discussed in the preceding paragraphs. It is conceivable that V1 was above the sector zone during this time. The interaction regions needed to explain the CRI decreases were not seen in the unipolar fields from the north polar coronal hole. However, interaction regions of limited latitudinal extent may be present in the sector zone slightly below the latitude of V1, and they would not be seen by V1. These interaction regions could produce CRI decreases that might extend to the latitude to V1 as a result of diffusion effects. If this hypothesis is correct, it could explain the apparent discrepancies between the V1 observations and 1) the scenario of *Webber et al.* [2009] as well as 2) the CR-B relation. A theoretical study of the latitudinal extent of CRI variations associated with fluctuations of B with more limited extent is needed to test this hypothesis.

6. Summary and Discussion

[35] We discussed the relationship between B and changes in the cosmic ray intensity (>70 MeV/nuc) observed by V1 and V2 in the heliosheath. Since 1981, in the supersonic solar wind between 10 and ~98 AU, it was observed that when B is strong the CRI tends to decrease and when the magnetic field is weak the CRI tends to increase ("the CR-B relation"). It came as a surprise, therefore, that for several months after V1 and V2 crossed the TS, this relationship did not seem to hold in the heliosheath.

[36] The CR-B relation does not describe the observations for several months behind the TS. Excluding V1 observations made close to the TS, taking the initial cosmic ray intensity at 2005.79, integration of the CR-B relation using the observations of B(t) gives a cosmic ray profile CRI′(t) that contains the basic features of the CRI profile observed by V1 from 2005.79–2010.24, namely, 1) a "plateau" in the CRI between 2005.79 and 2007.27, and 2) the monotonically increasing CRI from 2002.27–2010.24. It also explains a large depression in the CRI within the plateau as the consequence of a sinusoidal pulse with a region of very strong magnetic fields followed by a region of weak magnetic fields, which together were observed for at least 165 days.

[37] Excluding V2 observations in the subinterval from 2007.68–2008.6 close to the TS, the CRI profile observed by V2 from 2008.6–20010.28 is also described by the profile derived from the CR-B relation.

[38] We do not know why the CR-B relation does not apply for approximately one year after the TS crossings. Perhaps enhanced turbulence or a different nature of the turbulence behind the TS [*Burlaga and Ness*, 2009] is one factor. The exchange of particles between the heliosheath in the supersonic solar wind is another factor that should be considered. One reviewer suggested that the speed of the heliosheath flow is another factor, particularly following the V1 TS crossing, where the speed is known to have been low as a consequence of the inward motion of the TS. Another possibility, suggested by the second reviewer, is that the CR-B relation might be different in the sector zone and the unipolar zone. In the supersonic solar wind, the sector zone is disturbed by interaction regions produced by fast flows or taking slower flows and by merged interaction regions. *Opher et al.* [2011] suggested that in the heliosheath the topology of the magnetic field might be different in the sector zone than in the unipolar zone as a consequence of the production of closed magnetic bubbles produced by magnetic reconnection. We did not find a relationship between the magnetic sectors and the CR-B relationship, but this is a separate subject for future study. Clearly, there is much to be learned about relationship between the magnetic field and cosmic rays in the heliosheath, requiring both theoretical and observational studies.

[39] The modulation model of *Perko and Burlaga* [1987, 1992] is an extension of the "diffusive barrier model" of modulation developed by *Perko and Fisk* [1983]. The phenomenological CR-B relation describes the cumulative effects of all enhancements and depressions of the magnetic field strength, rather than simply the effect of a single diffusive barrier. The barrier models assume that the diffusion coefficient is inversely proportional to B, which implies a relation between CRI(t) and B(t) strength, as in the CR-B relation. The model of Perko and Burlaga has been extended to include drifts by *Potgieter et al.* [1993], *le Roux and Fichtner* [1997], *le Roux and Potgieter* [1995], *Luo et al.* [2011], and others [see the review by *Potgieter*, 2010] to describe modulation in the supersonic solar wind. Since we have shown that the CR-B relation is applicable in the heliosheath (away from the TS), it should be possible to apply diffusion/drifts models to the heliosheath and explain the CRI profile observed in the heliosheath by V1 and V2 as a function of the solar cycle and distance from the Sun.

[40] The diffusion/convection models involve both the flow speed V and the diffusion coefficient. It is standard practice to assume that the diffusion coefficient is inversely proportional to some power of the magnetic field strength B [e. g., *Florinski and Zank*, 2006]. Presumably, fluctuations

in the magnitude and/or direction of the magnetic field are responsible for the scattering that determines the mean free path and diffusion coefficient. Relating the diffusion coefficient to the observed fluctuations in B is a long-standing and difficult problem. This is particularly difficult in the heliosheath, where it is difficult to quantitatively describe the fluctuations in **B**. For example, is usually not possible to determine the power spectral of the fluctuations, owing to large data gaps each day, the nonstationary of the fluctuations, and difficulties in extracting the signal from the noise in small-scale the magnetic field fluctuations. Characterizing the small-scale fluctuations of B is a challenge and an ongoing subject of research.

[41] On a smaller scale, *Webber et al.* [2009] observed two sequences of three successive decreases in the CRI in the V1 data, which they attributed to an interplanetary shock observed at V2 and extending to the latitude of V1. They attributed the second CRI decrease to the arrival of a propagating interplanetary shock at V1.

[42] In the first sequence, a shock was not observed at V1, but a GMIR, possibly the same GMIR observed by V2, did pass V1 during the second CRI decrease, but this CRI decrease began ~40 days after the arrival of the GMIR. It is not sufficient to model the observations at V1 with a shock alone, excluding the GMIR. The relationship between the GMIR and the CRI decreases can only be understood by a model that also includes propagation effects.

[43] In the second sequence, the observations at V1 are not consistent with either the interpretation of *Webber et al.* [2009] or the CR-B relation. The expected increase in the magnetic field strength associated with the second CRI decrease was not observed by V1. Since V1 was in a unipolar region above the sector zone, it is possible that the scenario of Webber et al. and the CR-B relation are valid at latitudes slightly below that of V1, inside the sector zone, where a MIR of limited latitudinal extent might be present. Such an interaction region could produce CRI decrease at lower latitudes which could propagate diffusively to the latitude of V1 where they could be observed in the absence of a shock or MIR. A theoretical investigation is needed to evaluate the relevance of this hypothesis.

[44] **Acknowledgments.** T. McClanahan and S. Kramer provided support in the processing of the data. Daniel Berdichevsky computed the zero level offsets for the instruments. N. F. Ness was partially supported by NASA grants NASA NNX 07AW09G and NASA NNX 09AT41G to the Catholic University of America.

[45] Philippa Browning thanks the reviewers for their assistance in evaluating this paper.

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