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Voyager 2 Observations of Plasma and Pressure Pulses

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Abstract. This paper provides the latest data from Voyager 2 on plasma characteristics in the heliosheath including the observations of pressure waves in the plasma and particle data. Models and observations show that solar transients drive pressure waves through the heliosphere. Pressure pulses that could drive heliosheath waves are observed near the previous solar maximum upstream of the termination shock. We show that the most recent data is consistent with the presence of pressure waves and compare the heliosheath waves with the pressure increases in the heliosheath. The magnetic field is better correlated with density and galactic cosmic ray intensities in the supersonic solar wind than in the heliosheath. The galactic cosmic rays are correlated with the plasma and particles with a ~30-day lag in both the supersonic wind and heliosheath.

1. Introduction

Voyager 2 (V2) was in the heliosheath, 118 AU from the Sun, in April 2018 at a heliolatitude of 31° S. The Voyager 1 (V1) plasma instrument failed in 1980, so V2 is providing the first plasma data from this region. Observations show that the heliosheath flows are much faster at V2 than V1 and that the flows turn tailward more quickly [1]. Several studies predict that solar transients drive pressure waves in the heliosheath [2,3,4,5,6,7,8]. These pressure pulses are partially transmitted and partially reflected near the heliopause. The reflected waves again encounter the termination shock, moving it inward [4,5]. The transmitted waves drive weak shock waves into the local interstellar medium [3]. Since 2011, the heliosheath structure has been dominated by pressure pulses with correlated changes in the plasma density, temperature and speed and in the particle intensities at all energies but a with less strong correlation with the magnetic field B [9]. The source of these pressure pulses is likely MIRs (merged interaction regions) that dominate the outer heliosphere near solar maximum. This paper shows V2 data through April 2018 including the plasma parameters and the pressure pulses observed by both the plasma and particle instruments. The properties of the pressure pulses in the heliosheath are compared to those in MIRs in the supersonic solar wind in the outer heliosphere.

2. Recent Voyager 2 Data

V2 measures the plasma currents in the low-energy resolution L-mode that is best suited for heliosheath observations in four Faraday cups every 192 s. These spectra are fit with convected

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isotropic proton Maxwellian distributions to derive the plasma parameters. Figure 1 shows 25-day running averages of V2 plasma data in the heliosheath. The solar wind speed has remained on average constant at about 145 km/s. The radial speed has slowly decreased; a linear fit gives a decrease of 4.4 km/s/yr and the average V_R is now about 80 km/s. The flow angles initially rotated fairly rapidly tailward with the RT and RN angles (using the standard RTN coordinate system) reaching almost 60° and 30°, respectively, in 2014. Since 2014 the RT angle has not rotated further and the RN angle has gotten smaller. The density profile has shown numerous changes of 25-50% on time scales of several months, with larger increases in 2015 and 2018. The average density has increased since the beginning of 2016. The temperature of the thermal protons has remained steady and averages about 50,000 K.

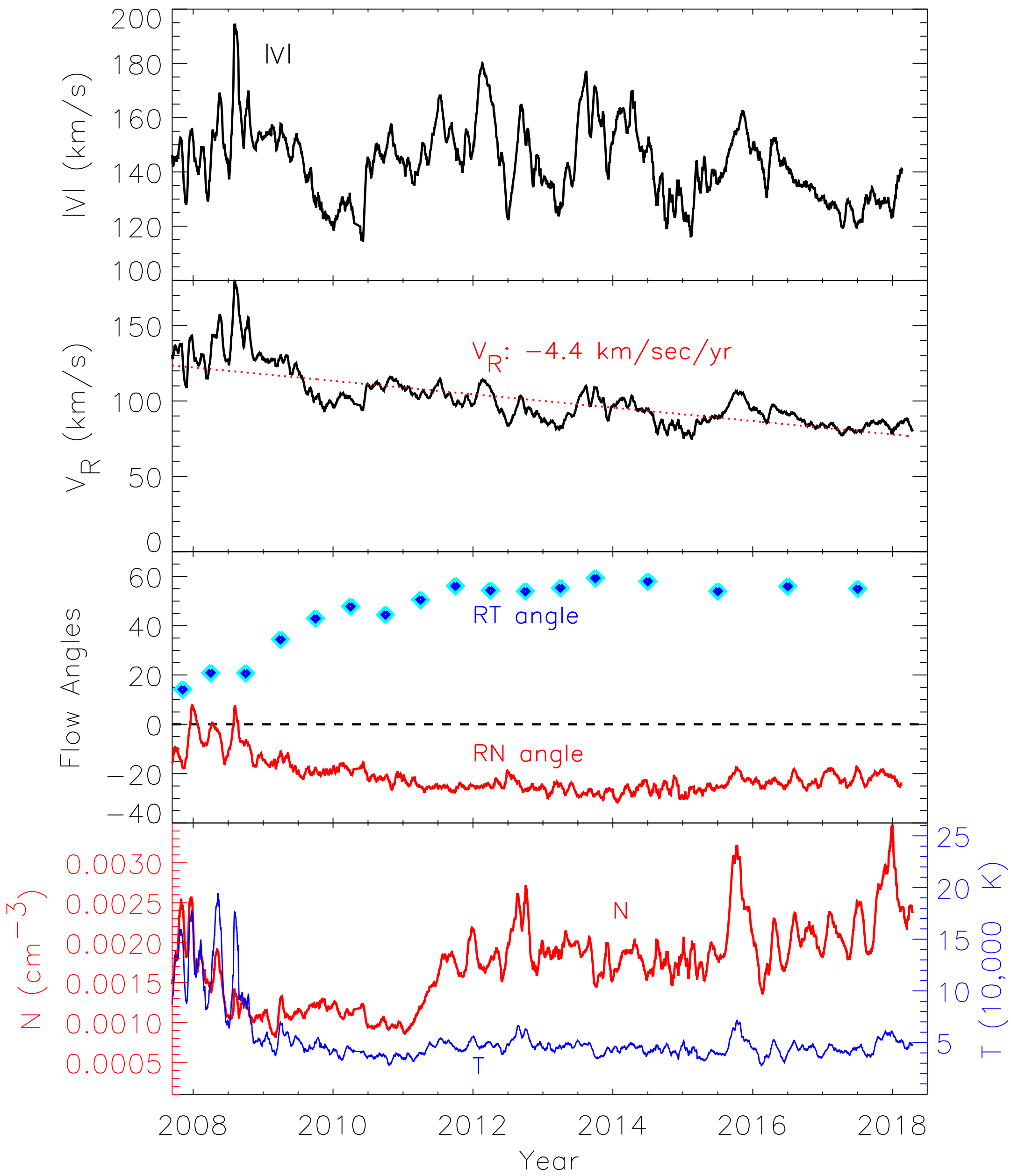

Figure 1. Plasma speed |V|, radial velocity V_R, flow angles, density N and temperature T.

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3. Pressure Waves in the Heliosheath

The density (pressure) increases after 2011 are often observed in the particle data as well in the plasma. The right panel of Figure 2 shows heliosheath data from 2010 to 2018; magnetic field data are so far available only through 2014. The plasma dynamic pressure profile is dominated by a series of enhancements starting in 2011, with the largest increase in 2015. The pressure pulses at 2012.6 and 2013.6 are associated with MIRs reported by the V2 magnetometer instrument [10, 11]. The 28-43 keV ion intensities from the Low Energy Charged particle (LECP) instrument and the >0.5 MeV/nuc ion and >70 MeV/nuc GCR (galactic cosmic ray) Cosmic Ray Subsytem (CRS) counting rates track the plasma pressure profile very well, with almost every pressure peak from 2011 into 2018 observed in the particle data as well. As discussed later, the lower energy particle and pressure peaks occur nearly simultaneously but the GCR peaks occur before the pressure peaks arrive at V2.

The sources of these pressure waves in the heliosheath are probably the MIRs that dominate the outer heliosphere at and after solar maximum [12]. The left panel of Figure 2 shows the pressure pulses observed by V2 during the previous solar cycle in the supersonic solar wind. These pressure increases were observed roughly twice per year and are associated with simultaneous increases in the magnetic field indicating that they are MIRs. The lower energy particles are not present in this region, but the GCRs again have peaks that precede the pressure and magnetic field increases.

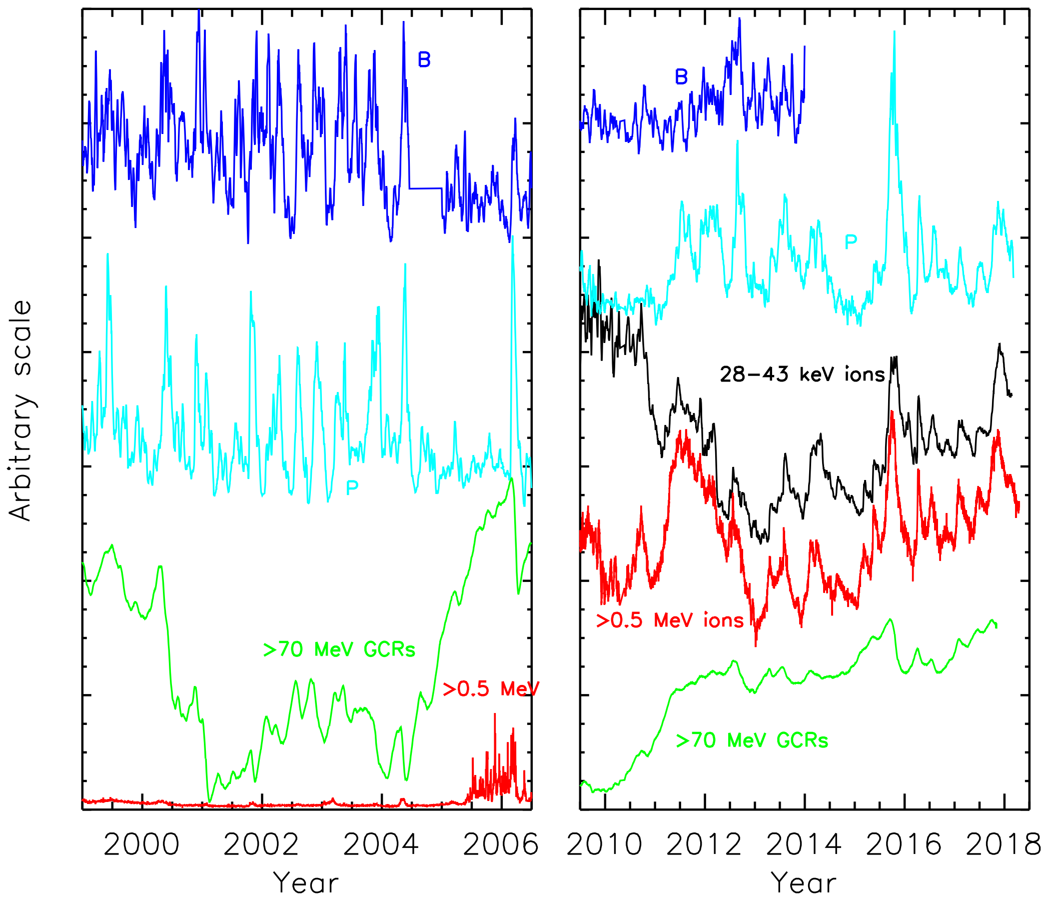

Figure 2. Fluctuations observed in MIRs in the supersonic solar wind (left) and in pressure waves in the heliosheath (right).

Figures 3 and 4 compare in more detail the pressure pulses in these two regions. Figure 3 shows the fluctuation amplitudes of the plasma density with other plasma, field, and particle measurements. Each

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panel has 25-day (1 solar rotation) running averages of (x - <x>)/<x> where x is the measured value and <x> is the 301-day average. The top panel compares the thermal proton density and temperature, which for a pressure wave would vary in phase since Tperp (to which V2 predominantly responds) changes due to conservation of the first adiabatic invariant as B increases. The correlation coefficient for N and T variations over the time period shown in the plot is 0.88 and peaks at a lag of zero. N and T are derived from the same fits to PLS spectra so are not independent quantities, but this correlation is not seen in the supersonic solar wind, only in the heliosheath.

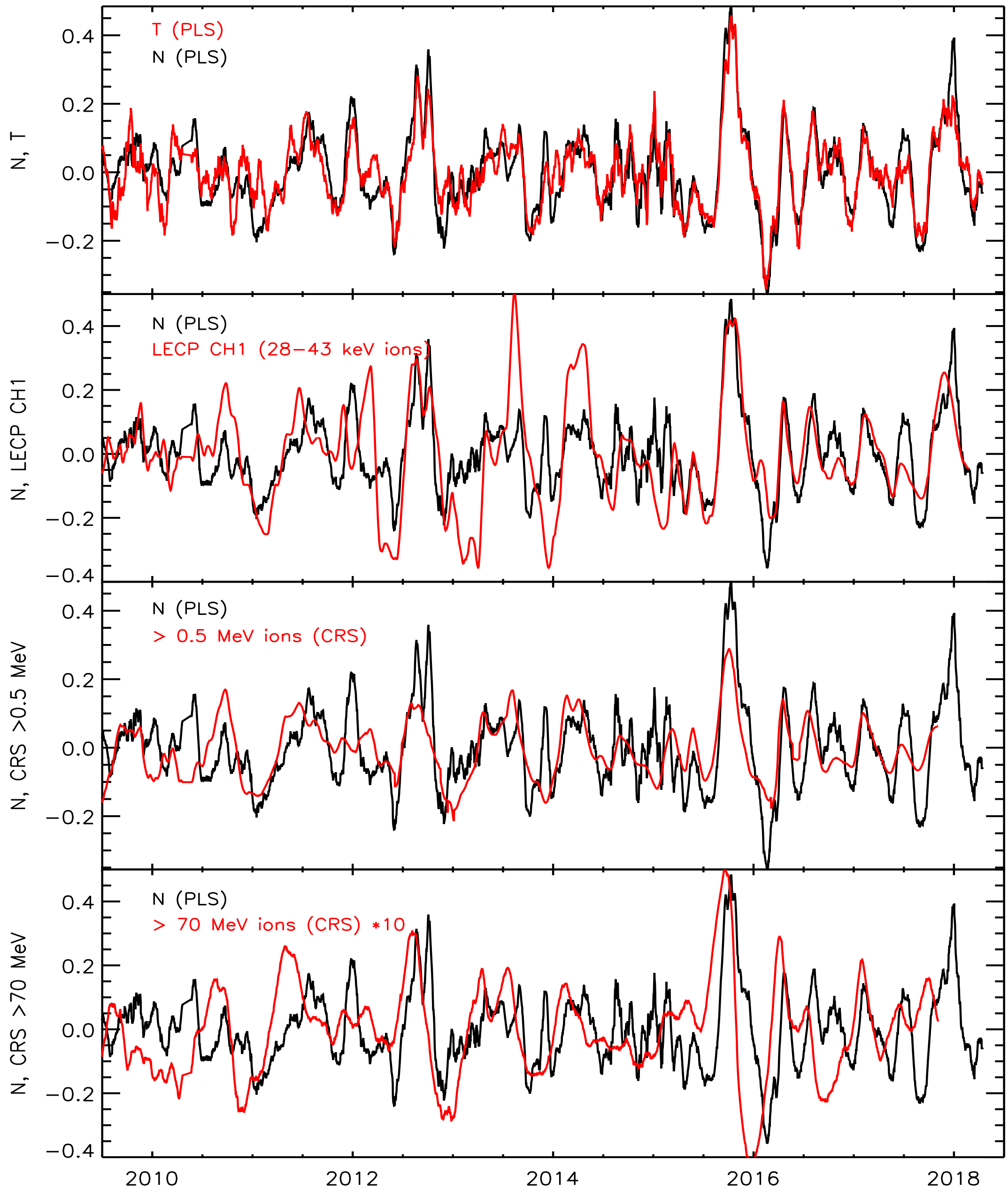

Figure 3. Changes in density (black curves) compared to changes in temperature and particle intensities (red curves) . The plots for each parameter x show (x-<x>)/<x> where <x> is averaged over 301 days.

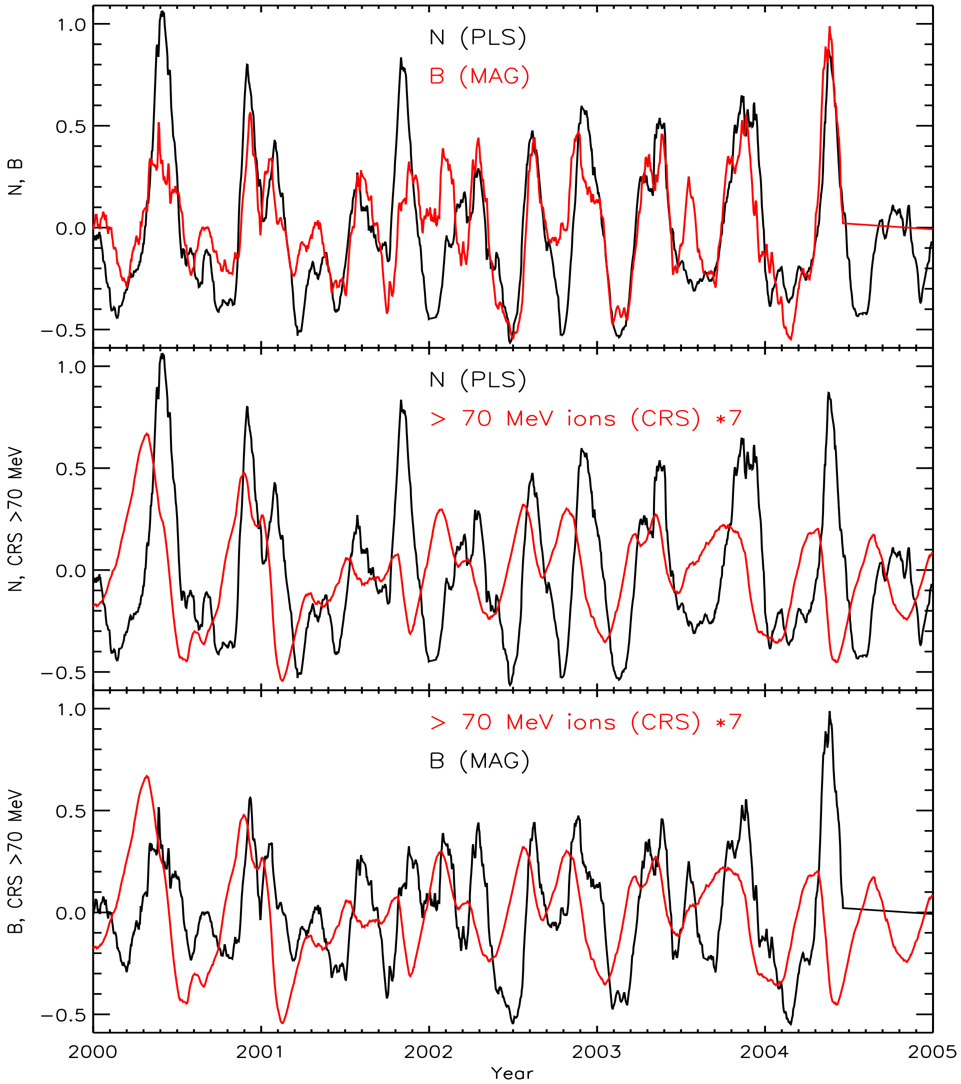

Figure 4. Comparison of fluctuations in N, B, and GCRs in MIRs in the outer heliosphere.

The second and third panels of Figure 3 compare fluctuations of density with the LECP 28-43 keV ion intensities and CRS >0.5 MeV ion count rates, respectively. If these changes are driven by pressure waves then the compressions (rarefactions) should increase (decrease) the energetic ion intensities roughly the same amount as the plasma density. Figure 3 shows that the amplitude of these changes are correlated and the magnitudes are similar; the >0.5 MeV/nuc rates vary less than the 28-43 keV intensities. The correlation between N and the 28-43 keV ion intensities is 0.60 with a lag near zero and between N and the >0.5 MeV/nuc ion count rates is 0.66 also with a lag near zero. The correlations are better in the recent data; for data after 2014.5 these two correlations are 0.77 and 0.80, respectively, indicating pressure waves are producing more of the observed variations.
The bottom panel compares N and the >70 MeV/nuc GCRs. The offset in the peaks is clear, with the GCR peaks occurring before the density peaks. The magnitude of the GCR variations is much less than those of the N variations (the GCR profile in Figure 3 is multiplied by 10). The correlation is 0.58 with a lag of 33 days. The GCR variations are not directly due to the pressure waves; they are likely due to the increased magnetic field associated with these waves inhibiting the transport of these waves

causing the GCRs to pile up in front of the pressure pulses, a mechanism which has been called the snow plow effect [13]. The correlation between N and B was found to be weak, 0.34, but magnetic after 2014 are not yet available.

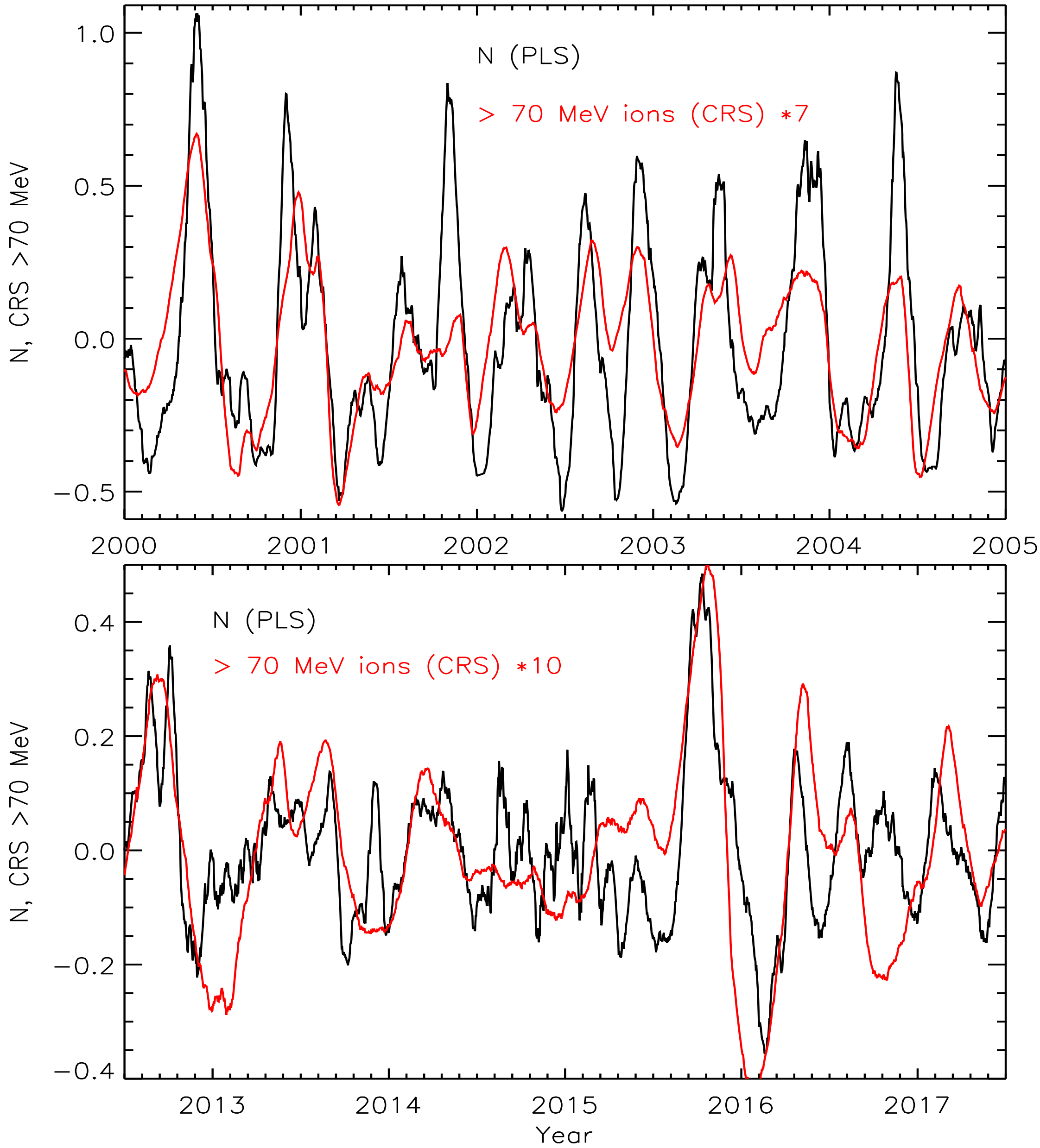

Figure 5. Comparison of fluctuations in N, B, and GCRs with a 33-day time shift.

Figure 4 shows comparisons of variations in the pressure increases (MIRs) observed in the supersonic solar wind from 2000-2005. The top panel compares N and B variations. The correlation is 0.79 with a lag of zero, much better than the 0.34 correlation in the heliosheath [9]. The bottom two panels compare N and B with the GCR counts; the GCR fluctuations are smaller than those of B and N as in the heliosheath and are multiplied by 7 in the figure. The GCR count rates features again lead the N and B features. The best correlation of N with the GCRs is 0.72 with a 33-day lag and for B with the GCRs it is 0.65 with a 30-day lag. Figure 5 shows the comparison of N with the GCRs in both the supersonic solar wind from 2000-2005 and in the heliosheath from 2012.5-2017.5 with the GCR data shifted by 33 days to show that this same shift best fits the data in both regions. The reason the same 33-day shift in the N and GCR profiles gives the best correlation is not known. The MIRs are propagating outward at 400-500 km/s in the supersonic solar wind. The heliosheath radial speed is about 100 km/s, although the pressure pulses could be propagating significantly faster [12]. The gyroradius of a GCR is about 0.1 AU; the solar wind moves this distance in roughly 10 hours so the 33-day shift seems not directly related to the gyroradius. The outward moving pressure and field increases are very large structures so their interaction with GCRs is complex.

4. Summary

This paper presents and discusses recent Voyager 2 observations. The plasma speed remains constant but V_R is decreasing slowly across the heliosheath. The flow directions, after initially turning tailward after the termination shock, have remained steady the past 4 years. Pressure waves continue to dominate the density profile; these waves are observed with similar magnitudes and phases in the keV and MeV particle data. The GCRs show changes correlated with the pressure waves but with smaller amplitudes and with a time shift of 33 days. Pressure increases in the last solar cycle in the supersonic solar wind show a better correlation between the magnetic field and other parameters (density and GCR intensity) than in the heliosheath. For reasons not understood, the GCR intensities lead the plasma density changes by 33 days in both the supersonic solar wind and heliosheath.

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