Periodicity of 151 days in outer heliospheric anomalous cosmic ray fluxes

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Abstract. Statistically significant variations have been observed in the differential flux of ~27-MeV anomalous cosmic ray (ACR) oxygen, helium, and protons at the Voyager 1 spacecraft during 1998 and 1999 (at a helioradius of ~73 AU). The quasiperiodic variations are in phase, with oxygen and helium having periods near 151 days, while protons exhibit a period of ~146 days. The Voyager 1 ACRs vary by ~30% with respect to the trend, and similar galactic cosmic ray variations, if they exist, must be less than ~5%, probably much less. No similar, significant periodicities have been detected for these same ACR species at Voyager 2 (at 57 AU) during this period. We report on these and other periodicities in the Voyager Low Energy Charged Particle experiment measurements and address the possible connection between this ~151-day ACR periodicity and the previously discovered ~154-day periodicities in solar flares, the interplanetary magnetic field, and other phenomena.

1. Introduction

Many authors during the previous two decades have observed periodicities ranging from ~150 to 158 days in a variety of solar and heliospheric measurements. *Rieger et al.* [1984] first identified such a variation in their report of a 154-day periodicity in the occurrence rate of solar gamma ray flares measured by the Solar Maximum Mission during 1980-1983. Subsequently, similar periodicities have been observed in other solar flare phenomena, such as X-ray measurements [*Bai and Sturrock*, 1987; *Brueckner and Cook*, 1990; *Dennis*, 1985], H_α flares [*Ichimoto et al.*, 1985], 10.7-cm radio flux [*Lean and Brueckner*, 1989; *Kile and Cliver*, 1991], other microwaves [*Bogart and Bai*, 1985], solar flare electron events [*Droge et al.*, 1990], proton flares [*Bai and Cliver*, 1990], and various solar flare indices [*Bai and Sturrock*, 1993; *Ozguc and Atac*, 1989]. In addition to these flare measurements, similar periodicities were also found in historical and modern sunspot measurements [*Lean and Brueckner*, 1989; *Lean* 1990; *Carbonell and Ballester*, 1990], solar diameter observations [*Delache et al.*, 1985; *Ribes et al.*, 1989], and auroral data [*Silverman*, 1990]. These investigations have confirmed the existence of this periodicity as a more general solar oscillation during solar cycle 21 (1976-1986) and suggest that similar periodicities exist in other recent solar cycles and historical data, although the status for other solar cycles is less certain than for cycle 21 [see, e.g., *Bai and Cliver*, 1990, Table 4]. Apart from these phenomena, observations have been made that indicate roughly 154-day periodicities in the near-Earth interplanetary magnetic field strength and solar wind speed [*Cane et al.*, 1998] and in solar proton events [*Gabriel et al.*, 1990]. Recently, recurrences in Ulysses spacecraft measurements of MeV proton fluxes and anisotropies were reported [*Dalla and Balogh*, 2000] that may also be related to these periodicities.

Cosmic ray measurements indicating periodicities near 154 days, however, have not yet been fully explored. *Kudela et al.* [1991] did analyze 3- and 6-month periodicities in data from the Calgary and Deep River neutron monitors but did not address periodicities near 154 days. Cosmic ray intensity measurements made at the Deep River neutron monitor and Huancayo ion chamber during 1947-1990 were examined spectrally by *Valdes-Galicia et al.* [1996], and a ~154-day peak is evident in their solar cycle 21 analysis, but, although aware of the work of *Ichimoto et al.* [1985], they did not investigate a relationship between the solar flare and cosmic ray periodicities. Likewise, three roughly 1/4-year-wide intensity variations were observed by *Decker et al.* [1999] in anomalous cosmic ray (ACR) H and He measurements at the Voyager 2 spacecraft in 1995, but no connection was examined between these small-amplitude variations and the 154-day solar periodicity. The cause of the 154-day solar and heliospheric oscillations is not yet known, although physical mechanisms that might explain the periodicities have been explored, such as (1) the global solar "clock" model of *Bai and Sturrock* [1993], (2) the suggestion that the period may be a manifestation of the timescale required for storage and emergence of magnetic flux through the solar surface [*Ichimoto et al.*, 1985; *Carbonell and Ballester*, 1990; *Cane et al.*, 1998], and (3) the beat frequencies of rotational rates proposed by *Wolff* [1983] to be due to solar "*g*-mode" oscillations.

In the present paper, 1998 and 1999 measurements from Voyager 1 (V1) and Voyager 2 (V2) are both visually and harmonically analyzed, revealing statistically significant variations in V1 ACR O, He, and H fluxes, all in phase with periods of ~151 days. This work appears to be the first to present evidence relating cosmic ray variations or outer heliospheric (>5 AU) measurements to the established 154-day solar and heliospheric

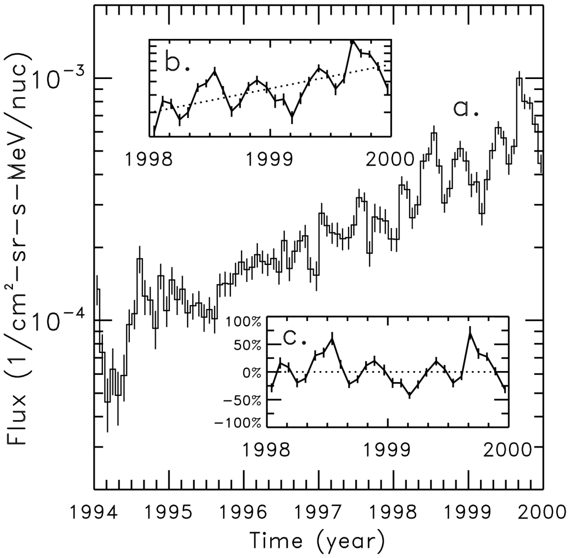

Figure 1. (a) The 26-day averaged flux of Voyager 1 anomalous cosmic ray (ACR) oxygen ions with energies of 0.65-2.64 MeV/nucleon for the years 1994-1999. (b) The inset highlighting the same data for the 1998-1999 period, where the dotted line indicates the exponential trend function. (c) The percentage residual intensity variation shown for the 1998-1999 period.

periodicities. The lack of such a periodicity is noted for V2 anomalous cosmic rays, although some other periodicities at V2 and V1 exist. In sections 2 and 3 the details of this analysis and the numerical observations are presented, followed by a discussion in section 4 of the physical implications of the anomalous cosmic ray periodicities.

2. Data Analysis

The Low Energy Charged Particle (LECP) experiments aboard the two Voyager spacecraft [*Krimigis et al.*, 1977] return composition and differential flux measurements of energetic ions (~0.3 to 30 MeV/nucleon) in the distant heliosphere. From the first day of 1998 to the last day of 1999 the helioradii of V1 and V2 increased from 68.9 to 76.3 AU and from 53.7 to 59.9 AU, respectively. During this period the heliolatitudes of the Voyagers changed from 33.3° to 33.6° N for V1 and from 18.4° to 21.1° S for V2. We use these LECP measurements (derived from dE/dx versus E pulse height data) to investigate the periodic behavior of the three ACR species for which we have sufficient counting statistics during 1998 and 1999 to allow meaningful periodogram analysis (see below). The kinetic energy ranges studied for these ACR protons, helium, and oxygen at V1 are 23.9-29.5, 2.99-11.5, and 0.65-2.64 MeV/nucleon, respectively, and 24.4-28.6, 3.71-12.3, and 0.60-2.13 MeV/nucleon, respectively, at V2. These energy ranges were selected to correspond with the ACR flux peaks (at ~27 MeV for each species) observed in the energy spectra of these particles during the period of 1994-1999 [*Hamilton et al.*, 1999].

Although the ~150-day flux variations of ~20-50% with respect to the trend were initially observed in 26-day averaged data (Figure 1a), 5-day averages are used for the bulk of our analysis, as these finer time-resolution data afford a high level of confidence in the statistical significance of the periodicities. The 1998-1999 period exhibited more nearly periodic ~150-day oscillations and larger-amplitude variations than other time periods in the 1994-1999 interval. Therefore this 2-year period was selected as the primary period of interest for this study; however, in 1997, although the "period" varies (Figure 1a), there are two or three additional cycles with a roughly 150-day period preceding the five cycles in 1998-1999. The approach to the analysis of these variations has been to first determine the trend function for the data (Figure 1b) and then to remove this trend, yielding the residual variations from the trend (Figure 1c). A linear least squares fit to the log of the flux, log $j(t)$, was used to determine the trend function, $f(t)$, having the form $f(\mathrm{t}) = N\exp[(t-t_\mathrm{o})/\tau]$, where t_o is the year 1998 throughout and N and τ (which correspond to the flux levels at the beginning of 1998 and the *e*-folding times, respectively) are determined by the fitting procedure. The residual intensity variation, $J(t)$, is defined by the relation, $J(t) = [j(t) - f(t)]/f(t)$. Residuals are plotted for both 26-day averaged (solid line) and 5-day averaged (open symbols) data in Figure 2. Before implementing the periodogram analysis, the data are further prepared by transforming to zero-mean time series.

The periodogram analysis method of *Scargle* [1982] has been used to harmonically analyze the periodicities in question, as it permits a straightforward interpretation of the statistical significance of a given periodicity and easily accounts for the few short data gaps in the 5-day averaged data. With this method the periodogram is determined, giving the spectral power, $P(\nu)$, at a given frequency ν. When normalized by the total statistical variance, σ_o^2, of the data [see *Horne and Baliunas*, 1986], the periodogram of *Scargle* [1982] has the useful property that the statistical significance at a single preselected frequency, ν, is determined by exp($-z$), where $z = P(\nu)/\sigma_\mathrm{o}^2$ is the normalized power, a dimensionless quantity. We indicate the statistical significance with the notation $n\sigma$, where σ is the Gaussian standard deviation, n is a numerical coefficient, and $p_\mathrm{sig}(n\sigma)$ (the integral of the Gaussian distribution, $\exp(-x^2/2\sigma^2)/(2\pi\sigma^2)^{1/2}$, from $x = -n\sigma$ to $x = +n\sigma$) is equal to the statistical significance. Therefore the normalized power is related to the statistical significance by $1\text{-}e^{-z} = p_\mathrm{sig}(n\sigma)$, as the σ labels on the right side of Figure 3 illustrate. Another useful measure provided by *Scargle* [1982] is the false alarm probability, $F=1\text{-}(1\text{-}e^{-z})^M$, which, for a periodogram with M independent frequencies, determines the probability of observing a single peak at or above a given height, z, assuming the data were pure noise; $p_\mathrm{o} = 1\text{-}F$ therefore gives the probability that a given peak with a maximum normalized power of z or higher is the result of a signal rather than noise. This probability, F, supplements the statistical significance by taking into account that a larger number of searched independent frequencies implies a larger probability for statistical fluctuations to generate an erroneous periodogram peak with power of a given level. With p_o = 99.7% and $z = -\ln(1\text{-}p_\mathrm{o}^{1/M})$, we found z = 9.0 to be the false alarm

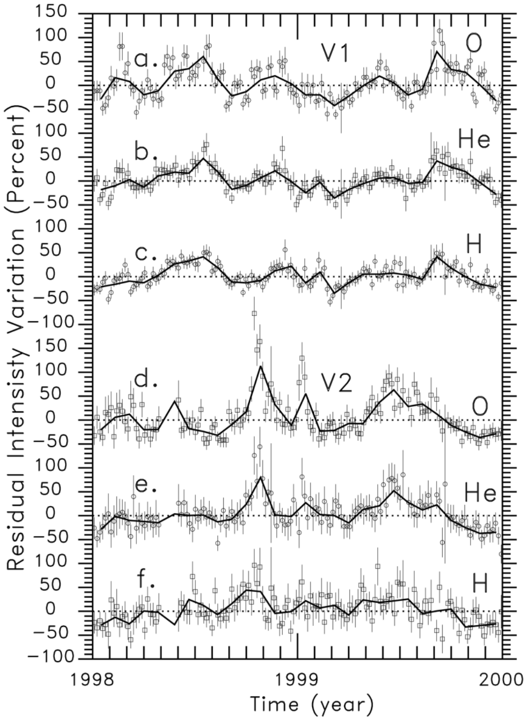

Figure 2. The 26-day averaged (solid line) and 5-day averaged (open symbols) ACR residual intensity variations are displayed for 1998-1999 Voyager 1 (a) oxygen, (b) helium, and (c) protons and Voyager 2 (d) oxygen, (e) helium, and (f) protons with respective mean energies of 1.6, 7.2, 27, 1.4, 8.0, and 27 MeV/nucleon.

threshold for the periodograms shown in Figure 3. This threshold uses M = 24, where M has been determined by calculating the number of Fourier frequencies [see *Scargle*, 1982, Appendix D] that lie within the 40- to 400-nHz frequency range (see below) of the periodograms in Figure 3. The frequency resolution, defined by the spacing, $\delta\nu$ = 15.8 nHz, between independent frequencies, is the inverse of the total analysis period, in this case two years. Therefore it follows that $M = \Delta\nu/\delta\nu + 1 = 24$, where $\Delta\nu$ = (400-40) nHz = 360 nHz is the frequency range interval. The alternate use of the empirical method of *Horne and Baliunas* [1986] to estimate the number of independent frequencies rather than that of *Scargle* [1982], results in a higher value for M since in this case the frequency spacing, $\delta\nu_{\mathrm{HB}}$, is smaller than that given above. This is determined from $\delta\nu_{\mathrm{HB}} = \Delta\nu'/(M'-1)$ = 6.07 nHz, where $\Delta\nu'$ = (1157.4-15.8) nHz = 1141.6 nHz is the unrestricted frequency interval defined by the Nyquist frequency and the inverse of the 2-year analysis period and M' = 189 is the number of independent frequencies obtained with the *Horne and Baliunas* [1986] method for time series with 146 data points (the number of data points in a 2-year series recorded at 5-day intervals). With this we find $M_{\mathrm{HB}} = \Delta\nu/\delta\nu_{\mathrm{HB}} + 1 = 60$, resulting in the somewhat higher false alarm threshold of z = 9.9, but this is an unimportant distinction for our purposes, so we retain the previously determined threshold. Although we show only the results of periodogram analysis of the 5-day averages in Figure 3, we also performed power spectral density analysis [see *Press et al.*, 1989], based on a discrete Fourier transform, as well as periodogram analysis, on the 26-day averages, finding essentially the same results, with nearly identical peak centers and widths.

It is important to note that although a fine-frequency grid has been employed, resulting in the smooth appearance of the periodograms in Figure 3, the meaningful frequency resolution remains, nevertheless, constrained by the independent, or Fourier, frequencies. We have $\delta\nu$ = 15.8 nHz, which is comparable to the typical peak widths and peak spacing in the periodograms in Figure 3. This somewhat coarse frequency resolution, due to the relatively short 2-year analysis period relative to the 151-day period, limits our ability to distinguish between pure and quasiperiodicities, on the basis of the periodogram, unless the scale of the peak or spectral feature is significantly larger than 16 nHz. However, one may still return to the time domain and obtain a measure of the pure or quasiperiodic nature of a variation by comparing features in adjacent cycles of the time series, as is done in section 4. The lower limit of the 40- to 400-nHz frequency range in Figure 3 was selected as a compromise choice between requiring either two or three complete cycles during the 2-year analysis period. The 2-cycle (32 nHz) threshold is of use since, with fewer than two cycles of repetition, an accidental coincidence of two time-intensity features cannot reliably be distinguished from a true periodicity, while the 3-cycle (48 nHz) minimum provides added confidence by ensuring agreement among two or more periods between adjacent, repeated time-intensity features. The 400-nHz upper limit was chosen so as to yield an order-of-magnitude range as well as to exclude frequencies higher than a frequency (445 nHz) defined by our customary 26-day averaging interval.

In addition to ACRs we analyzed two other particle populations accessible to the LECP instrument to see if they also exhibited ~150-day periodicities: interplanetary (IP) accelerated particles and galactic cosmic rays (GCRs). Conditions in the outer heliosphere for IP ions such as ~1-MeV protons are still quiet during 1998 and 1999, so statistical limitations are significant. Therefore despite the fact that hints of an anticorrelation between (0.63-1.39 MeV) IP H and ACR O are seen at V1, a periodicity in interplanetary accelerated particles cannot be concluded on the basis of visual inspection of the 26-day averaged IP H time-intensity profile (not shown). Periodogram analysis of 5-day averaged V1 IP H (not shown) does reveal a very broad, barely significant spectral feature near 160 days. To study GCRs, we visually and harmonically analyzed the LECP Eβ05 counting rate provided by R. B. Decker (private communication, 2000), which is sensitive to protons with energies greater than 70 MeV, as well as other high-energy ions. The 5-day averaged Eβ05 time profiles (not shown) are very similar for both V1 and V2 to the ACR data in Figure 2 (although the ~5% Eβ05 variations are small compared to the ~30% ACR H variations), and periodogram analysis of the V1 data does show a statistically significant ~150-day periodicity.

However, an estimate of the relative ACR and GCR contributions to this rate based on the ~2- to 400-MeV H spectrum at V1 during 1998 [*Stone et al.*, 1999] indicates that the ~5% variations in the >70-MeV H data could be due to variations of the higher-energy ACRs (which dominate GCRs up to ~120 MeV) contributing to the Eβ05 rate. Therefore we can rule out a large-amplitude (> 5%) GCR periodicity, but our inability to separate ACRs from GCRs at these higher energies prevents us from determining whether small-amplitude GCR variations might exist. (We note that independent 1998-1999 Voyager 1 measurements given in Figure 2 of *McDonald et al.* [2000] do reveal the ~151-day periodic features in 30- to 56-MeV ACR H but not in 130- to 225-MeV GCR H, although this is not addressed by the authors.) These results suggest that although ACRs appear to most clearly display the ~151-day periodicity during the 1998-1999 time period, other particle populations may exhibit less significant but related variations.

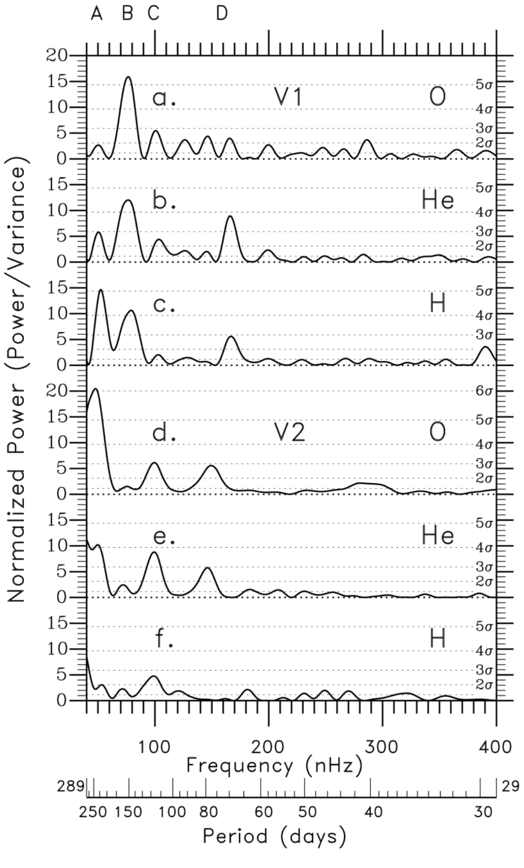

Figure 3. Periodograms of the 1998-1999 5-day averaged ACR time series from Figure 2 displaying the normalized power versus frequency (and wave period) for Voyager 1 (a) oxygen, (b) helium, and (c) protons and for Voyager 2 (d) oxygen, (e) helium, and (f) protons. Sigma labels and dotted lines indicate statistical significance levels in terms of the Gaussian standard deviation. A, B, C, and D above Figure 3a indicate the peaks labeled in Table 1.

3. Observations

At Voyager 1, significant ~151-day periodicities were found for ACR O, He, and H, as evidenced by the large peak near 76-79 nHz in Figures 3a, 3b, and 3c. Oxygen (Figure 3a) has a peak at 151±12 days (77±6 nHz), with a 5.3σ statistical significance. (The periodogram peak uncertainties are estimated throughout by the full-width half-maximum divided by 2.35, as their near-Gaussian forms suggest.) In the helium data (Figure 3b) a peak is found at 152±15 days (76±7 nHz) with a 4.5σ significance; and the proton periodogram (Figure 3c) has a peak at 146±15 days (79±8 nHz), with a statistical significance of 4.2σ. The conclusion that these three significant peaks are related to one another, in addition to the threefold agreement of their periods (within uncertainties), is strongly supported by the fact that the three variations are in phase (Figures 2a-2c). For oxygen and helium these peaks are the most significant, but there is a proton peak of 221±21 days (52±5 nHz) that has a higher normalized power than the 146-day H peak, and it is above the z=9 false alarm threshold. There are a few peaks at or below the false alarm threshold that are, nevertheless, noteworthy, as comparable periods are found in multiple species. The 221-day H peak mentioned above is mirrored by a ~3σ helium peak at 229±18 days (51±4 nHz) and a similar, though nonsignificant, oxygen peak around 231 days (50 nHz). Anomalous protons and helium have peaks with ~3-4σ significance at 69±2 days (167±6 nHz) and 70±2 days (166±5 nHz), respectively; again, there is also a similar nonsignificant oxygen peak at 70 days (166 nHz). For comparison with potentially related V2 peaks the following small V1 O, He, and H peaks are mentioned: 115±5 days (101±5 nHz), 112±6 days (104±6 nHz), and 112±5 days (103±4 nHz), respectively, with only the oxygen peak nearing 3σ and the others being less significant.

For Voyager 2 the situation is different. No significant peaks were found with periods near 151 days, although statistically insignificant peaks at 153 days (76 nHz), 160 days (72 nHz), and 162 days (71 nHz) can be identified in the ACR O, He, and H periodograms, respectively (Figures 3d-3f); peaks with higher significances, though at or below the false alarm threshold, are evident for oxygen and helium, both at 116±8 days (99±7 nHz), with 3σ and ~4σ significance, respectively, along with a less significant H peak at 117±9 days (99±8 nHz). The largest feature in the V2 periodograms is the oxygen peak of 243±41 days (48±8 nHz) with a 6σ statistical significance, although barely three cycles of this period are analyzable in the 2-year 1998-1999 interval. While there appears to be a more complicated dual-peak structure for He and H, these species show similar peaks at 231 days (50 nHz) and 216 days (54 nHz), respectively. Longer-term analysis of the 26-day averaged V2 oxygen 1994-1999 time series shows a ~2.5σ peak centered on 230 days, indicating that the 243-day O peak is not a sustained, prominent feature. Finally, there are two more subthreshold peaks, with ~3σ significance for O and He at the respective peaks of 77±4 days (150±8 nHz) and 79±4 days (146±7 nHz). These observations for V1 and V2 ACR oxygen, helium, and protons are summarized in Table 1. Note that were it assumed that the observed periodic variations are due to disturbances that propagate radially outward from the Sun with a speed of 800 or

400 km/s (for typical “fast” or “slow” solar wind), then the Doppler shift due to the spacecraft motion would result in a 2% or 4% increase, respectively, of the period measured at the spacecraft relative to the true period. Since neither the manner nor the speed of propagation is known and the estimated Doppler corrections are small (relative to the measurement uncertainties), throughout this paper we report the actual periods measured in the spacecraft frames without adjustment.

4. Discussion

It is the primary result of this work that a statistically unambiguous periodicity has been identified in multiple outer heliospheric anomalous cosmic ray species, with a period of ~151 days, as detailed in sections 2 and 3. Before addressing the important secondary result that this periodicity is observed only at the higher northern latitude of V1 and not at the lower southern latitude of V2, the issue will be addressed of how these ACR variations might be related to the 154-day solar periodicities first reported by *Rieger et al.* [1984]. The most likely medium connecting the “Rieger periodicities” with those in the distant heliosphere is the interplanetary magnetic field (IMF). *Cane et al.* [1998] have shown that the near-Earth IMF strength exhibited a 153-day periodicity during 1978-1982 (during solar cycle 21) that is in phase with concurrent solar periodicities, in particular, solar energetic particle events. This result provides a plausible mechanism for explaining the periodic ACR variations since it is expected [*Burlaga et al.*, 1985] that a strong anticorrelation should exist between the IMF and cosmic ray intensities (although the very weak magnetic field in the vicinity of V1 will probably make it difficult to directly detect the expected IMF periodicity).

Returning to the comments from section 2, it happens that the extent to which the ACR periodicity is quasiperiodic also provides some support for the IMF interpretation given above. To determine how uniform the periodicity is during 1998 and 1999, V1 oxygen was examined in more detail. To facilitate determination of the time intervals between adjacent local maxima and minima, the 5-day data (Figure 2a) were smoothed using several boxcar averages ranging from 25 to 65 days, and then the peak and trough of each cycle were visually identified. The local maximum or peak-to-peak period was found to be 140±46 days, while the local minimum or trough-to-trough period was determined to be 154±18 days. There are two interesting aspects of this result: (1) The intensity minima have an average period that is consistent with the periods observed for the various solar periodicities, while the intensity maxima have a somewhat shorter average period (although the overlapping standard deviations prevent a conclusive determination), and (2) the standard deviation of the minimum period is less than half as large as the maximum-period standard deviation; thus the minima are more uniformly periodic. This is consistent with variations in the interplanetary magnetic field strength causing the ACR periodicity, as it is the elevated IMF strength that periodically inhibits the flow of the cosmic rays into the high-IMF region, resulting in the decreased particle intensity at the spacecraft.

Table 1. Period (in Days) of Selected Periodogram Peaks From Figure 3

S/C	ACR	Peak A, 48-54 nHz	Peak B, 71-79 nHz	Peak C, 99-104 nHz	Peak D, 146-167 nHz
V1	O	231	151±12 [a,b]	115±5	70
V1	He	229±18 [a]	152±15 [a,b]	112±6	70±2 [a,b]
V1	H	221±2 [a,b]	146±15 [a,b]	112±5	69±2 [a]
V2	O	243±41 [a,b]	153	116±8 [a]	77±4
V2	He	231 [a,b]	160	116±8 [a,b]	79±4 [a]
V2	H	216	162	117±9	...

[a] Indicates statistical significance at or above the 3σ level.
[b] Indicates that the 99.7% false-alarm threshold has been met.

The LECP Eβ05 counting rate, sensitive to >70-MeV H, and the GCR measurements of *McDonald et al.* [2000] constrain potential 151-day variations in GCRs at V1 during 1998-1999 to less than ~5%, probably much less, while the ACRs vary by 20-50%. Therefore it is interesting to consider which physical quantities relevant to cosmic ray transport and modulation might distinguish GCRs from ACRs. The velocities, β, relative to c, for the ~27-MeV ACR H, He, and O we analyzed are 0.23, 0.12, and 0.06, respectively, and the particle rigidities, R, are 0.22, 0.45, and 0.87 GV, respectively. For the 180-MeV GCR H and 1280-MeV GCR He observed by *McDonald et al.* [2000], the values of β are 0.54 and 0.67, respectively, and the values of R are 0.60 and 1.69 GV, respectively. The overlapping rigidities between the anomalous and galactic cosmic rays suggest that the R dependence is not the primary factor determining the occurrence of the 151-day periodicity. Conversely, the values of β for the ACRs are quite distinct from the GCR values, as are the total energies, indicating that these parameters may be important in organizing the 151-day periodic phenomenon.

Why is the 151-day periodicity evident only at V1? The heliospheric environments in which the Voyager spacecraft reside are quite different, beyond merely the magnitudes and signs of the respective helioradii and heliolatitudes of the twin spacecraft. As *Burlaga and Ness* [2000] have pointed out, V2 in 1998 is in the “sector zone,” meaning that the V2 latitude is less than the tilt angle of the heliospheric current sheet (HCS), and therefore V2 repeatedly crosses and recrosses the HCS as the wave pattern of the HCS ripples past the spacecraft; thus, during each solar rotation period, V2 alternately samples the northern and southern halves of the heliosphere, which have opposing magnetic polarities. This is in contrast to V1, which *Burlaga and Ness* [2000] show is largely outside the sector zone, and therefore the spacecraft remains predominantly north of the HCS, sampling a single IMF polarity. It has been reported [*Lean*, 1990, and references therein] that the existence of a ~154-day periodicity in the southern solar hemisphere is questionable. A southern periodicity with a different phase or period (or no related periodicity at all) could explain the lack of a 151-day periodicity at V2 in two ways: (1) Complications imposed by the repeated sampling of distinct northern and southern periodicities as Voyager 2 crosses the HCS might obscure the variations, rendering them incoherent or undetectable, or (2) the fact that V2 is primarily south of the HCS might imply that a relevant periodicity is simply nonexistent in that region of the heliosphere. We point out that peaks B and C from Table 1 are candidate northern and southern periodicities, with ~151 days for the north and ~116 days for the south. It would be interesting to learn if comparable periods are found in solar phenomena of the northern and southern hemispheres during 1998 and 1999, as this could rule out or support explanation 1. A search for future periodicities after V2 leaves the sector zone can test both explanations 1 and 2 as well.

Recent data so far indicate that the Voyager 1, 151-day periodicity appears not to continue into the year 2000. This would imply that the 5- to 8-cycle periodic ACR episode has a 2- to 3-year duration (depending on whether one included the pseudo-periodic start-up phase in 1997), which is consistent with previous work [*Lean*, 1990] finding typically 1- to 3-year episodes of the periodicity. We also examined 26-day averaged V1 O data from 1994-1999 and found, except for one 3σ, high-frequency (~370 nHz) peak, that the only peak significantly higher than 2σ was a ~3σ peak of ~160 days (72 nHz). This shows, as was found by *Cane et al.* [1998] in the IMF, that the periodicity has a period that is dependent on the time interval studied. Some indications consistent with 22-year heliomagnetic variations in the periodicities are found in the literature, such as the lack of a 153-day periodicity in the IMF during the even cycles 20 and 22, compared with the existence of this periodicity during cycle 21 [*Cane et al.*, 1998] and the existence of a 5.1-month peak in neutron monitor data during cycle 21 but not cycle 20 [*Valdes-Galicia et al.*, 1996]. Moreover, *Lean* [1990] reports disproportionate occurrences of alternating north-south periodicity episodes in sunspot areas during odd solar cycles, and many authors have observed that the power of the Rieger periodicity during cycle 21 is greater than that during 20 and 22, when it is observed. The present episode of a 151-day periodicity in the ACR fluxes takes place during the rising phase of solar cycle 23. (Nominal "1 AU" times are used here to relate the present observations to the solar cycle.) It would be interesting to see if other phenomena, particularly IMF and other cosmic ray measurements, exhibit similar periodic behavior during this period and how they compare with the previous odd solar cycle.

A periodicity in the global solar magnetic field perhaps related to the rate of magnetic flux emergence, such as that discussed by *Cane et al.* [1998] or *Ichimoto et al*. [1985], appears to more naturally explain subsequent ACR variations than the solar flare "exciters" of *Bai and Sturrock*'s [1993] "clock" model. Yet, it is of note that the three most significant V1 peaks at 70, 151, and 221 days could be interpreted as being subharmonics of the 25.5-day fundamental period of the clock model, with the third, sixth and ninth integer multiples of this period corresponding to subharmonics of 76.5, 153, and 229.5 days, respectively. We feel, however, that it is premature, before confirmation of the 151-day ACR periodicity by additional cosmic ray or outer heliospheric measurements, to draw any conclusion concerning the cause of the Rieger periodicities.

5. Summary

We have presented evidence of statistically significant ~150-day periodic variations in the intensities of three species of ~27-MeV anomalous cosmic rays measured at the Voyager 1 spacecraft during 1998 and 1999. These outer heliospheric ACR oxygen, helium, and proton variations are all in phase, have periods in agreement with one another, and have amplitudes of ~30% with respect to the trend. The most prominent variation is seen in ACR oxygen, with a period of 151±12 days. We interpret the ACR periodicities as being related to the well-known (though not well understood) solar periodicities first detected by *Rieger et al.* [1984], which have comparable periods ranging from ~150 to 158 days. The interplanetary magnetic field strength, which was shown by *Cane et al.* [1998] to sometimes exhibit this Rieger periodicity, is most likely related to the ACR variations, probably by periodically impeding the transport of anomalous cosmic rays as regions of elevated magnetic field strength propagate past the spacecraft. We find that GCR ions do not show large ~150-day variations, but we cannot rule out related GCR variations of less than ~5% with respect to the trend. The lack of similar, significant periodicities at Voyager 2 was also reported. This is perhaps due to complications arising from the proximity of Voyager 2 to the wavy and rapidly varying heliospheric current sheet and to observed differences [*Lean*, 1990] between periodicities in the northern and southern hemispheres of the Sun.

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