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ON THE PHASE OF THE 27 DAY MODULATION OF ANOMALOUS AND GALACTIC COSMIC RAYS AT 1 AU DURING SOLAR MINIMUM

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ABSTRACT

We report on the 27 day oscillations in the intensities of He and O ions of the anomalous cosmic rays (ACRs) observed near Earth by the *Wind* spacecraft during the 1995–1997 solar minimum period. Oscillations persist throughout the period with amplitudes as large as 50%. Galactic cosmic ray (GCR) oscillations, observed by neutron monitors, are in phase with the ACRs, but with much smaller amplitude (2%–3%). For a sustained period of almost a year, peak intensities occur near north-to-south crossings of the heliospheric current sheet and valleys near south-to-north crossings. In GCR observations in the 1974–1976 solar minimum, 27 day oscillations with a similar phase are seen. Understanding these observations poses a severe challenge for models of solar modulation as well as for models of the solar and heliospheric magnetic fields.

Subject headings: cosmic rays — interplanetary medium — solar wind — Sun: magnetic fields

1. INTRODUCTION

A 27 day periodicity in the intensity of Galactic cosmic rays (GCRs) was first observed by Forbush (1938) and was recognized as a signature of the synodic rotation period of the Sun. However, 10 years would pass before it became clear that the modulation was interplanetary and did not merely result from a change induced in the geomagnetic field (e.g., Simpson 1998). Later, evidence was found that GCR intensities tended to peak near the heliospheric current sheet and decrease with heliomagnetic latitude (Newkirk & Lockwood 1981). This observation conflicted with the drift theory of modulation that prevailed at the time (Jokipii & Thomas 1981) and prompted Kóta & Jokipii (1983, 1991) to include diffusion in the model, which could produce a maximum in intensity at the current sheet.

In recent years, 27 day modulations have been observed in anomalous cosmic-ray (ACR) He as well as in GCRs by the *Ulysses* spacecraft during its transit in heliolatitude from pole to equator to pole of the Sun (e.g., McKibben 1998). The relationship between the amplitude of the oscillations and the heliolatitude gradients was studied by Zhang (1997) and Paizis et al. (1999). These authors found a maximum in the amplitude of the 26 day (sidereal) oscillations of ~30% at a particle rigidity near 1 GV. The observation of the 27 day oscillations near Earth, on *Ulysses*, and even on the *Voyager* spacecraft (Decker et al. 1999) in the outer heliosphere shows them to be extensive in scope.

In this Letter, we examine the intensities of ACR He and O observed near Earth on the *Wind* spacecraft during the solar minimum from 1995 to 1997. We compare these ACR observations with GCR intensities recorded by the Climax neutron monitor of the University of Chicago. Comparisons are also made with the interplanetary magnetic field and solar wind speed measured on the *Wind* spacecraft.

2. OBSERVATIONS

Measurements of ACR intensities are made with the Low-Energy Matrix Telescope (LEMT) in the Energetic Particles Acceleration, Composition, and Transport experiment on the *Wind* spacecraft, launched 1994 November 1 (von Rosenvinge et al. 1995). The response of LEMT to ACR ions and the ACR ion spectra during this solar minimum were discussed at length by Reames (1999a; see also Reames 1999b).

Figure 1 compares particle intensities and solar wind speed during the first 3 months of the years 1995 and 1996. During 1995, we see strong high-speed streams, especially near February 1 and March 1, accompanied by increases in the intensity of 4–8 MeV amu^{-1} He. These strong streams produce shock waves at corotating interaction regions (CIRs) outside 1 AU where the He is accelerated. Even at strong CIR events, the spectra do not extend to high energies and O is rarely affected, especially above 8 MeV amu^{-1}. Note that depressions in the ACR O accompany the increases in He during these high-speed streams. Other increases in He and 4–8 MeV amu^{-1} O during this period (e.g., January 11 and March 22) are from solar energetic particle (SEP) events. While 27 day oscillations of the 8–18 MeV amu^{-1} ACR O are clearly seen during this period, the role of shocks at the CIRs during this period may be as much a factor as the global heliospheric field in producing these oscillations.

By way of contrast, the 1996 period in Figure 1 shows a weaker stream structure with no acceleration of He at CIRs, yet a 27 day modulation remains. Unfortunately, the remaining period of 1996 and early 1997 is not as quiet as that in early 1996, but despite a few SEP events, there are few strong CIRs.

The top panel in Figure 2 shows He and O intensities on an expanded scale appropriate for quiet periods when ACRs dominate. At times during the infrequent and relatively brief SEP and CIR events, intensities—especially that of He—simply move off scale. This strategy is the opposite of that of Reames (1999a), in which all periods with hints of He increase were surgically removed, even though O may have been unaffected by the small SEP or CIR events. Times of moderately large events that affect low-energy O are indicated as black triangles along the abscissa of the top panel. The bottom panel shows count rates of the Climax neutron monitor so that intensity variation of GCRs may be compared with those of the ACRs.

Figure 2 shows that the ~27 day oscillations are present for essentially all of the 20 month period shown and that they are present in the same phase, but with different amplitudes, in ACRs and GCRs. While the duration covered by Figure 2 was

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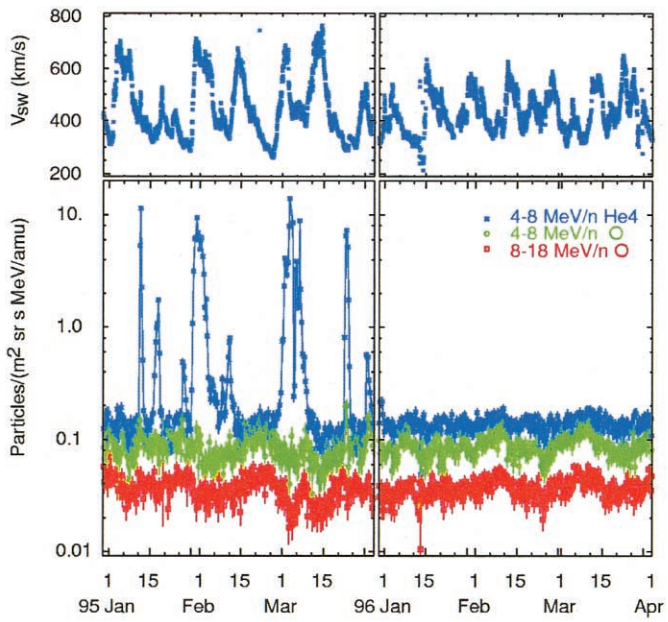

FIG. 1.—Intensities of He and O (8 hr averaged) at the indicated energies observed on the *Wind* spacecraft are shown as a function of time in the bottom panels for the first 3 months in 1995 (*left*) and 1996 (*right*). The solar wind speed is shown in the top panels during corresponding time intervals.

limited to provide clarity, we see no time when the oscillations disappear; i.e., the current sheet is never "too flat" to produce oscillations. For ACR O, the amplitude of the oscillations can be extremely large; the intensity maximum can be over twice that of the neighboring minima.

Figure 3 attempts to correlate the phase of the ACR O oscillations with the magnetic polarity and the transit times of the current sheet. The middle panel shows magnetic field azimuth to display the sector structure. Red or violet colors near ∼300° mark fields that are directed sunward along the Parker spiral; these fields emerge from the southern solar hemisphere. Azimuths near ∼120° are green or blue-green in color and mark outward fields from the northern hemisphere on the Sun. These colors indicating field direction at each time are mapped onto the intensities of the 8–18 MeV amu^{-1} O in the bottom panel and onto the solar wind speed in the top panel.

The ACR intensities show a strong tendency to rise when the spacecraft is connected to the northern (*green*) solar hemisphere and fall when connected to the southern (*red*) solar hemisphere. Thus, *current sheet crossings occur near both the maxima and the subsequent minima of ACR intensity*. This behavior occurs during the brief four-sector period in 1996 June and July as well as in the later two-sector oscillations, although brief departures from the pattern do exist. The fluctuation near 1996 December 1 occurs during an SEP event (with an accompanying coronal mass ejection).

Note that the solar heliographic equator is inclined by 7°.25 to the ecliptic so that the Earth spends 6 months (June 8–December 7) above the solar equator and 6 months (December 7–June 8) below. This is the primary reason that the field

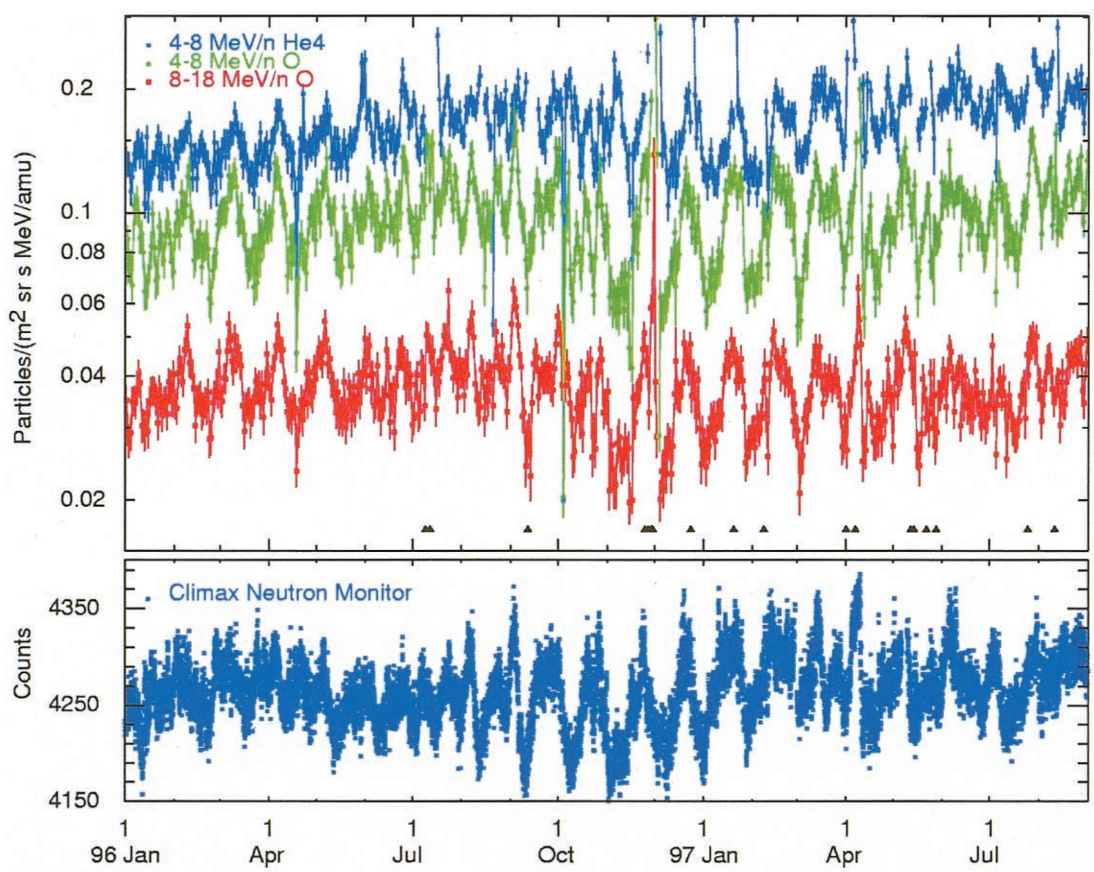

FIG. 2.—Intensities of ACR He and O at the indicated energies observed on the *Wind* spacecraft are shown (*top panel*) as a function of time for a 20 month period in 1996 and 1997, showing 27 day oscillations. Count rate of the Climax neutron monitor, plotted in the bottom panel, shows related GCR oscillations.

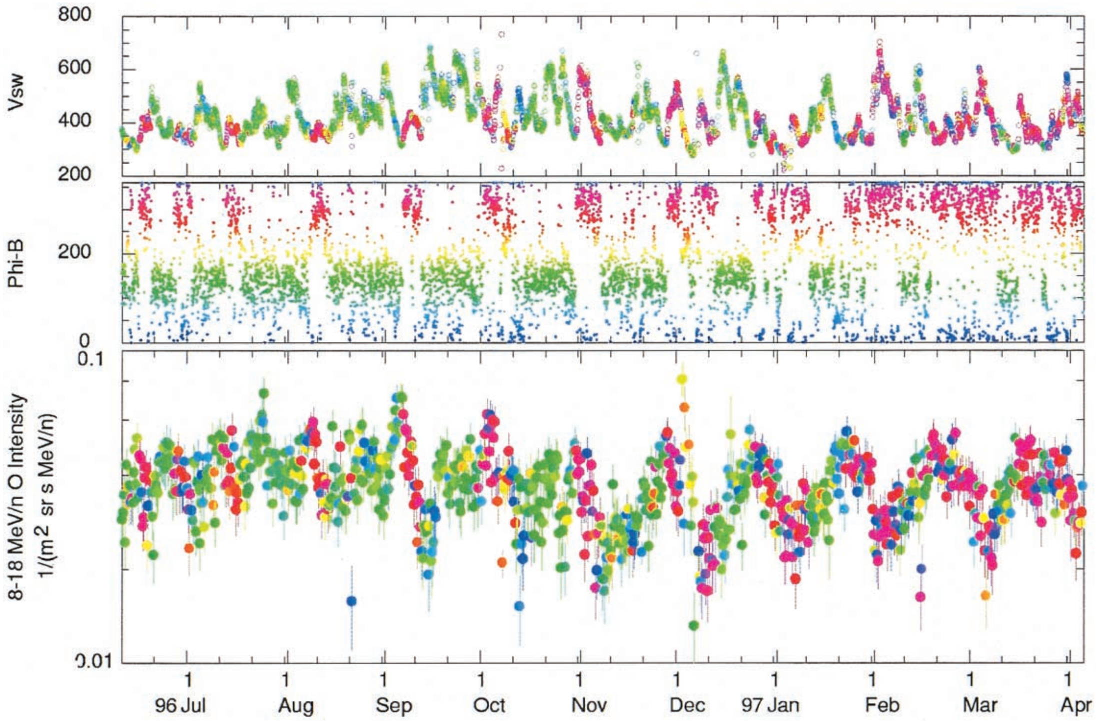

FIG. 3.—*Middle*: Azimuth angle of the magnetic field vs. time. Color scheme marks outward fields near ∼120° (*green*) and sunward fields near 300° (*red*). The 8 hr averaged ACR O intensity and the solar wind speed, colored by the magnetic azimuth, are plotted in the bottom and top panels, respectively. Rising ACR intensities are predominantly green and falling intensities red, with current sheet crossings near both maximum and minimum intensities.

direction is mostly outward (*green*, northern) during the first part of Figure 3 and mostly inward (*red*, southern) toward the end of the period. Inward fields almost completely dominate the first half of 1996 so that the sector structure disappears; hence, it cannot be used to mark the oscillations during that period. However, we observe no sustained period when the phase is opposite that shown in Figure 3; intermittent periods with the same phase are seen during 1995 and even in 1998, despite increased SEP activity.

3. DISCUSSION

Early modulation theories (Kóta & Jokipii 1983, 1991) offered no explanation for the phase of the 27 day oscillations that we observe. More recent models (Kóta & Jokipii 2001a, 2001b) appear capable of explaining the behavior with suitable choice of parameters. Kóta & Jokipii (2001a) obtain variation similar to that observed, but with opposite phase. Using a more complex model of the heliospheric current sheet, Kóta & Jokipii (2001b) find 27 day modulation closer in phase to that observed. However, the small tilt angle of the heliospheric current sheet during our observations (13°–26°) and the absence of CIR-accelerated ions impose important constraints on these models.

A priori, the modulation resulting from a more complex model of the solar field, such as the Fisk (1996) model (Fisk, Zurbuchen, & Schwadron 1999), offers the potential of explaining the observations. In this model, footpoints of field lines migrate slowly from high latitude to low latitude (see Fig. 3 in Fisk et al. 1999) so that the field lines sampled by the *Wind* spacecraft might extend to high latitudes beyond 1 AU, where they would sample higher GCR and ACR intensities during this $A > 0$ phase of the solar cycle.

Consider first the case when the spacecraft is near the solar equator (June or December) so that inward and outward fields are equally sampled as the Sun rotates. With the Fisk model (Fisk et al. 1999), field lines extending to the highest northern latitudes (within ∼20 AU) are encountered just before the spacecraft crosses the current sheet from north to south (*green to red*). However, field lines extending to the highest southern latitudes are encountered just before the spacecraft crosses the current sheet from south to north (*red to green*). Thus, we would expect the ACR and GCR intensities to peak near every current sheet crossing, even if cross-field diffusion were included.

When the Earth is above the heliographic equator (June to December), field lines extending to high latitudes would be seen before the north-south (*green-red*) transit of the current sheet, as described above, but fields near the south-north transit would remain nearer the current sheet. This would be consistent with the observed 27 day modulation. However, when the Earth is below the ecliptic (December to June), field lines near the south-north (*red-green*) transit would reach the highest latitudes and attain maximum ACR intensity. This reversal in phase is not observed. Apart from phase, the Fisk model offers great potential for explaining the 27 day variations. Modifying the longitudinal dependence of the field model may be required to explain the data.

To verify that the phase behavior we observe is not unique to the present epoch, we have examined GCR intensities during the previous two solar minima. Intensities of 121–230 MeV protons from the Goddard experiment on the *IMP 8* spacecraft are shown in Figure 4, colored by the magnetic azimuth, for the 1975 solar minimum ($A > 0$). These data show some of the same predominant phase relationships seen in the ACR data in Figure 3; rising GCR intensities are predominantly green and falling intensities red. After the middle of 1975, this behavior becomes difficult to follow because of the four-sector structure during some periods and the lack of current sheet

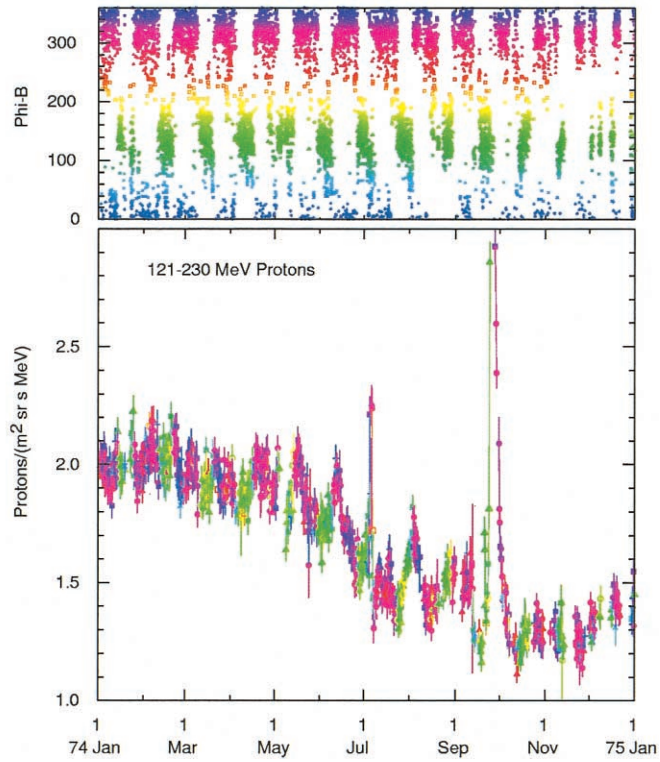

FIG. 4.—*Top*: Azimuth angle of the magnetic field vs. time. Color scheme marks outward fields near ∼120° (*green*) and sunward fields near 300° (*red*). The 8 hr averaged proton intensity from *IMP 8*, colored by the magnetic azimuth, is plotted in the bottom panel for the year 1974. Rising GCR intensities are predominantly green and falling intensities red, with current sheet crossings near both maximum and minimum intensities.

crossings during others. During the years 1986–1987 ($A < 0$), the amplitude of 27 day GCR oscillations is extremely small (Richardson, Cane, & Wibberenz 1999), and the phase cannot be established. The difference in amplitude of the 27 day oscillations between $A > 0$ and $A < 0$ cycles (Richardson et al. 1999) has not been explained. No adequate ACR observations are available at 1 AU during these earlier epochs.

4. CONCLUSIONS

Measurements of ACR He and O near Earth surrounding the 1996 ($A > 0$) solar minimum show strong 27 day oscillations in intensity throughout the entire period of solar minimum. Modulation of the Galactic cosmic rays is similar in phase but lower in amplitude. Peaks of the particle intensities occur near north-to-south crossings of the current sheet, and valleys occur near south-to-north crossings. This phase is not observed to change when the observer crosses the heliographic equator.

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[2] See http://ulysses.uchicago.edu/NeutronMonitor/.

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