Low Energy (0.5-5.0 MeV/nuc) Anomalous Cosmic Rays at High Heliolatitudes and in the Ecliptic Plane

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Abstract

In 1997 to early 1998, anomalous cosmic ray (ACR) oxygen (O) was measured by the HI-SCALE instrument on the Ulysses spacecraft at 5 AU in the ecliptic plane for the energy range 0.5–5.0 MeV/nuc. At 1 AU in the ecliptic at this time (measured by the EPAM instrument on the ACE spacecraft) ACR O was only seen in the energy range 2–5 MeV/nuc. The radial gradient for 2–5 MeV/nuc ACR O was large, ~40%/AU, for days 242–305, 1997. By mid-1998, no ACR O could be measured in the entire energy range.

1. Introduction

Investigations of anomalous cosmic rays (ACR) during the decline of the 22nd solar cycle have benefited from the distribution of instrumented spacecraft in the solar system (Klecker and Mewaldt, 1998). These spacecraft range from ACE, SOHO, and SAMPEX near 1 AU in the ecliptic plane to the two Voyager spacecraft in the distant heliosphere. The Ulysses spacecraft has provided, for the first time, ACR measurements out of the ecliptic plane over both the north and south solar polar regions (e.g., Trattner et al., 1995a,b; 1996; Fr̈anz et al., 1995; Keppler et al., 1996; Lanzerotti and Maclennan, 1995; Lanzerotti et al., 1996; Maclennan and Lanzerotti, 1998; Marsden et al., 1999).

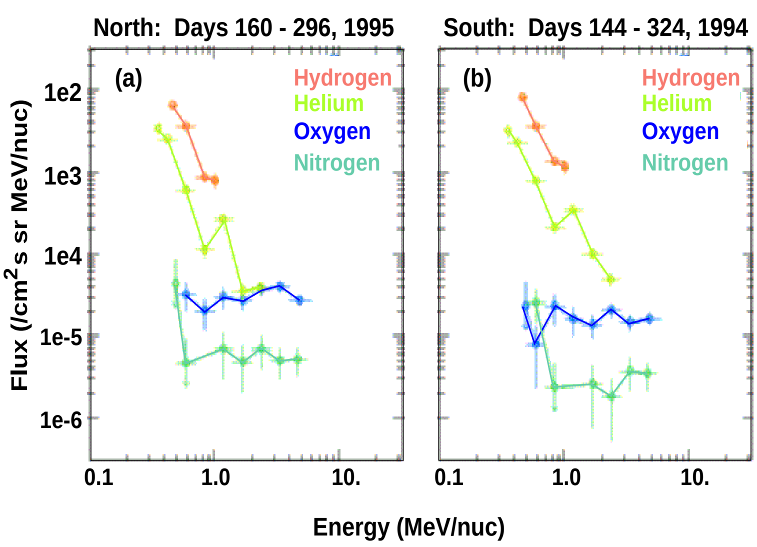

Fig. 1. Ion spectra above 65° heliolatitude

The interplanetary and ACR particle measurements reported here were acquired with the essentially identical Wart (W) composition telescopes in the HI-SCALE and EPAM instruments that were flown on the Ulysses and the ACE spacecraft, respectively. The Wart is a three-element solid state telescope that has a 5 μ first detector element followed by two 200 μ detectors that are used in coincidence and anti-coincidence to define the mass and the species of the detected ions (Lanzerotti et al., 1992). A pulse height analysis (PHA) is applied to individual events in order to provide good species and energy resolution. Two events are analyzed for each spin rotation of the spacecraft. Eight fixed energy channels, two each for hydrogen, helium, CNO, and Fe-group are also included.

2. High Heliolatitude ACR Oxygen and Nitrogen

The two lower curves in each panel of Figure 1 (adapted from Lanzerotti et al., 1996) are spectra of ACR oxygen (O) and nitrogen (N) for HI-SCALE measurements (0.5–5.0 MeV/nuc) made at heliolatitudes > 65°. Also shown are interplanetary hydrogen and helium spectra for each interval. Except for the lowest energy N values, the O and N spectra at these high heliolatitudes are essentially flat over this energy range. Furthermore, the O and N fluxes over the northern solar polar latitudes are about a factor of two larger than those measured over the southern solar polar latitudes (the measurements in the south were made approximately one year earlier). Maclennan and Lanzerotti (1998) attributed this to a temporal dependence of the access of ACR to the heliosphere: it might be expected that more ACR would be measured during the northern solar polar passage of Ulysses because the solar activity was substantially less than during the southern solar polar pass.

3. In-ecliptic ACR: 1–5 AU

Shown in Figure 2 are the intensities of O fluxes (2.8–6.0 MeV/nuc) measured on both HI-SCALE and ACE for the interval from the launch of ACE (day 242, 1997) to day 325, 1998. The

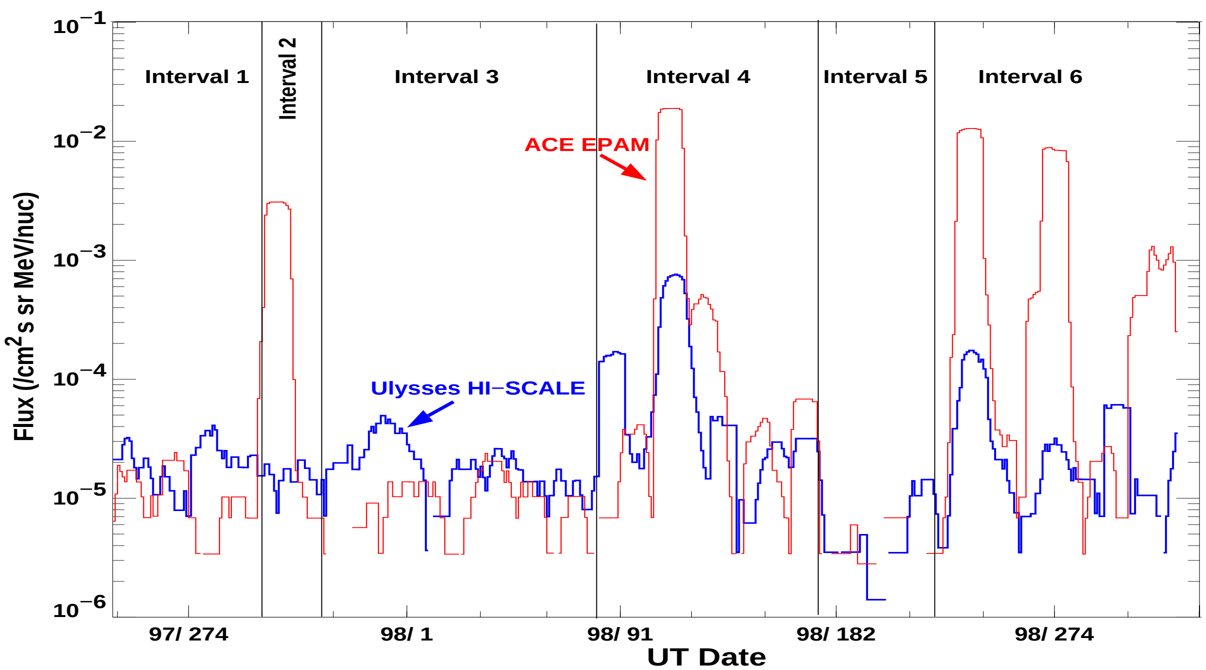

Fig. 2. 2.8–6.0 MeV/nuc oxygen fluxes

fluxes that are plotted are 11-day averages around the day of interest. During this time, Ulysses was at ~5.4 AU distance from the Sun and covered the latitude range from ~5°N to ~17° S. Six separate intervals are indicated in the Figure, largely defined by the level of particle activity that was measured at ACE. It is evident that the fluxes of O in this energy range were larger at Ulysses than they were at ACE during the intervals of less interplanetary activity, especially Intervals 1 and 3. Interval 5 is of particular interest in that the fluxes of O in the energy range shown dropped to quite low levels at both locations.

The evolution of the O spectra during the time period of Figure 2 is shown in Figure 3 for spectra acquired in intervals 1, 2, and 5. At Ulysses, just north of the ecliptic plane at ~5.3 AU in Interval 1, the O spectrum above ~1 MeV/nuc is essentially flat (to within the statistics), and is similar to the spectra in Figure 1. The two lower energy O flux values in this spectrum are upper limits. The $\gtrsim$1 MeV/nuc fluxes in this O spectrum during this interval are larger by a factor of about 2 than those measured at high northern latitudes (Figure 1). In contrast, the O spectrum at ACE is flat only above ~2.2 MeV/nuc, and rises sharply at the lower energies. These lower energy O fluxes are consistent with solar origin. At the highest energies, the ACE O fluxes are about 1/7 those measured at Ulysses. Essentially no ACR N fluxes (not shown here) were measured at Ulysses during Interval 1, in contrast to the situation found at the highest latitudes (Figure 1). The HI-SCALE O spectra in Interval 3 (not shown here) were also flat for E $\gtrsim$2 MeV/nuc, but with values about a factor of 2 less than in Interval 1. That is, between Intervals 1 and 3, the ACR fluxes at 5 AU had decreased following the solar activity that occurred during Interval 2.

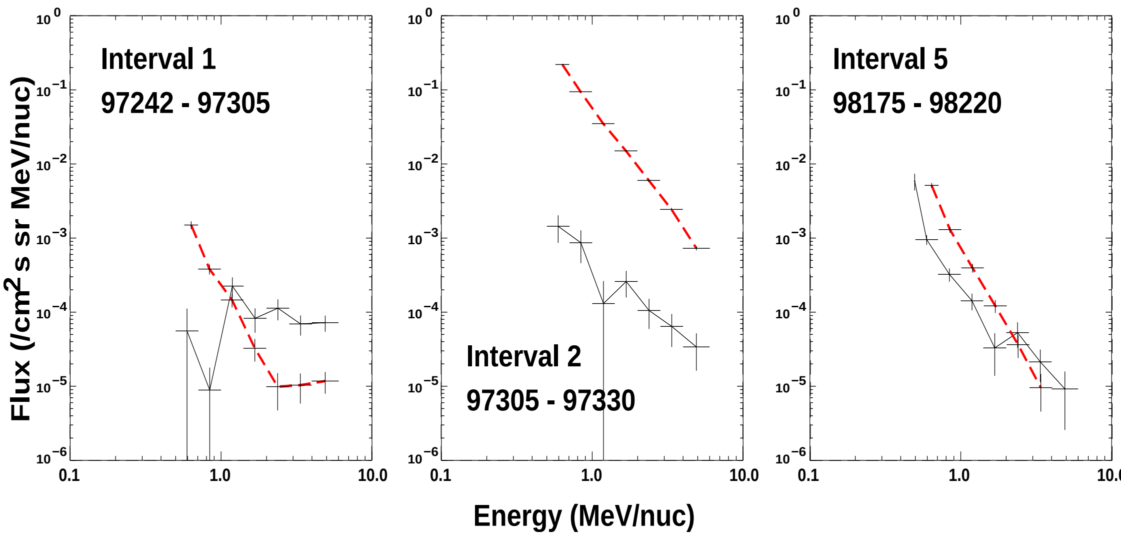

Fig. 3. Oxygen spectra in three time intervals (dashed, ACE; solid, Ulysses)

The HI-SCALE and EPAM O spectra in Intervals 2 and 5 have, roughly, inverse power law spectra across the energy band. In Interval 2, the radial gradient for O at the highest energies has reversed, with larger fluxes at ACE than at Ulysses at all energies. The Ulysses O fluxes for E $\gtrsim$ 1 MeV/nuc in Interval 2 are comparable to, or smaller than, the fluxes in Interval 1. The two lowest energy fluxes are more than a factor of 10 larger than the upper limits in Interval 1.

In Interval 5 the O fluxes are roughly inverse power laws and more similar at the two locations than in Interval 2. The O fluxes are larger at 1 AU than at 5 AU for E $\lesssim$ 2 MeV/nuc. Above this energy, the fluxes are comparable at both locations but smaller than they were in Interval 1. In both Intervals 2 and 5, the radial gradient is largely outward from the sun, showing the importance for solar particle input to the inner heliosphere in these periods. The small values of the highest energy O fluxes at Ulysses in Interval 5, compared to the fluxes at these energies in both Intervals 1 and 3, indicate that the increase of solar activity in Intervals 2 and 4 has caused a removal of the

ACR O (0.5–5 MeV/nuc) in the inner heliosphere to at least 5 AU.

4. Conclusions

Comparisons of the spectra (0.5–5.0 MeV/nuc) of interplanetary O at 1 and 5 AU in the ecliptic plane, and with ACR O spectra obtained at high heliolatitudes, indicate that ACR O fluxes persisted at 5 AU in the ecliptic plane for a longer interval of the declining phase of solar cycle 22 than did similar energy fluxes measured at 1 AU. At 1 AU, the lowest energy O (0.5–2.0 MeV/nuc) spectra resembled that expected from solar particles or from interplanetary acceleration by CIRs and traveling shocks. During Interval 1, the radial gradient (determined as per McKibben, 1989) of ACR O between 1 and 5 AU was large, ~40%/AU for the energy range 2–5 MeV/nuc. This value, much larger than the more typical ~18%/AU inferred from higher latitude (and somewhat higher energy) Ulysses measurements (Marsden et al., 1999), is probably evidence of the beginning of the disappearance of in-ecliptic ACR O at 1 AU at the onset of the new solar cycle. The large radial gradient deduced here would not be typical of quiet time, solar minimum conditions in the inner heliosphere.

The MeV-energy ACR O fluxes were not detected at 5 AU during Interval 5, following the considerable solar activity that was measured at both 1 and 5 AU in Interval 4. After mid-1998, ACR ions in the energy range covered by HI-SCALE were no longer measurable in the ecliptic plane of the heliosphere to distances up to 5 AU from the Sun. It will be interesting to see if HI-SCALE measures low energy ACR O at higher heliolatitudes as Ulysses climbs back to the southern solar pole in the next years.

Concerning the nitrogen measurements, although the statistics are poor, it is found that in Intervals 1 and 5, for $E \gtrsim 2$ MeV/nuc (probably ACR), the N fluxes at 1 and 5 AU are roughly comparable. In Interval 2, large fluxes of N (roughly an inverse power law spectrum) are measured at 1 AU, which are obviously of solar origin; at 5 AU, the N fluxes are more than a factor of 50 less. More details on the in-ecliptic ACR N results will be presented elsewhere.

Acknowledgments

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