Proceedings of ICRC 2001: 4247 © Copernicus Gesellschaft 2001

ICRC 2001

The 1992–2000 recovery of anomalous cosmic ray oxygen throughout the heliosphere

M. E. Hill[1], D. C. Hamilton[1], J. E. Mazur[2], and S. M. Krimigis[3]

[1]Department of Physics, University of Maryland, College Park, Maryland, 20742, USA
[2]Space Sciences Department, The Aerospace Corporation, El Segundo, California, 90245, USA
[3]Applied Physics Laboratory, Johns Hopkins University, Laurel, Maryland, 20723, USA

Abstract. Differential energy spectra and time-intensity profiles of anomalous cosmic ray (ACR) oxygen are presented for 1- to 29-MeV/nucleon ions observed in the inner and outer heliosphere. New low-energy measurements from the Low-energy Ion Composition Analyzer (LICA) instrument aboard the SAMPEX spacecraft, along with published low- and high-energy data from the SAMPEX, WIND, and ACE spacecraft, provide thorough 1-AU coverage of interplanetary ACR oxygen from 1993 to 1998. Outer heliospheric measurements of 0.3 - to 30-MeV/nucleon ACR oxygen are determined from data returned by the Low Energy Charged Particle (LECP) experiments on the Voyager 1 (V1) and Voyager 2 (V2) probes from 1992 to 2000. These measurements extend the simultaneous time- and energy-dependent study of ACRs to lower energies than previously analyzed throughout the heliosphere and, in particular, comprise the most complete examination of the recovery of low-energy ACR ions during the positive heliomagnetic polarity ($A > 0$) phase of the 22-year solar cycle. We find the data to be consistent with dominantly diffusive transport of ACRs from the outer to the inner heliosphere, a relativley constant ACR source flux during the recovery period after ~1994, and a significant spatial component to the large exponential increases in low-energy ACR oxygen at V1 and V2 from 1994 to 2000 resulting from spacecraft motion.

1. Introduction

It is generally believed that the so called anomalous component of cosmic rays is composed of ambient interstellar neutrals that penetrate the heliosphere, become "pick-up" ions by solar photoionization or charge exchange with solar wind plasma, are subsequently convected outward with the solar wind until undergoing acceleration at the solar wind termination shock (TS). From the TS the ACRs are thought to be transported both into and out of the heliosphere. This interpretation, although persuasive, presently lacks direct experimental confirmation at the acceleration stage. In particular, the TS has yet to be encountered by spacecraft, preventing a direct test of this region as the anomalous cosmic ray source, and the nature of the ACR source is not yet well understood, for example, in terms of its time dependence, geometry and motion. The transport of ACRs is also generally thought to be fairly well understood in terms of convection with the solar wind, diffusion resulting from interaction with the turbulent interplanetary magnetic field (IMF), and curvature and gradient drifts in the large scale IMF. The relative importance of these processes, however is not known.

Since there are still unresolved questions regarding the acceleration and transport of ACRs throughout the heliosphere, it is important to make studies from as many perspectives as possible. To wit, the low-energy portion of the ACR spectrum requires further attention. In this paper low-energy ACR oxygen is studied in the inner and outer heliosphere as a function of time, energy, and position. Comparisons are made with higher-energy measurements and together an expanded understanding of the transport and acceleration of ACRs in the heliosphere is sought.

Correspondence to: M.E. Hill (hill@umdsp.umd.edu)

2. Data Analysis

The anomalous oxygen measurements herein were made in three heliospheric regions: 1 AU – ecliptic measurements, outer heliospheric – northern heliolatitudes, and outer heliospheric – southern heliolatitudes. The new 1-AU data are from LICA, a time-of-flight mass spectrometer aboard the SAMPEX Earth-satellite, supplemented by published data from various instruments aboard the SAMPEX, ACE and WIND near-Earth spacecraft. The outer heliospheric data are from the LECP experiments on Voyager 1 and Voyager 2. From 1992 to the end of 2000 V1 varies in heliographic radius from 47 to 80 AU, and in heliographic latitude from 32º N to 34º N. During this period the V2 coordinates range from 36 to 63 AU and 5º S to 22º S. In 1996, the time period of the Voyager spectra shown in Fig. 1, the V1 and V2 coordinates are approximately 64 AU, 33º N and 49 AU, 16º S, respectively. The radial and latitudinal positions of V1 and V2 are displayed in Fig. 2c and Fig. 2d, respectively, as a function of time.

Energy spectra for anomalous cosmic ray oxygen are shown in Fig. 1 at three heliospheric positions. The 1-AU data below 10 MeV/nucleon are from the Earth-orbiting SAMPEX/LICA sensor while the SAMPEX satellite was at high geomagnetic latitudes, where interplanetary (IP) ions are well observed. The spectrum is averaged over the six-year period from 1993 to 1998, and subject to the quiet-time constraint that the LICA measurement of daily-averaged 0.6-0.85 MeV/nucleon ^{4}He flux is less than 0.02 particles/cm^2-sec-sr-MeV/nucleon. The diamond symbols in Fig. 1 represent the IP oxygen spectrum, including the low-energy component composed of solar energetic particles (SEPs) and ions accelerated in corotating interaction regions (CIRs). To obtain a time history of low-energy ACR oxygen (Fig. 2a), yearly averaged SAMPEX spectra were analyzed and the SEP/CIR components (below ~2 MeV/nucleon) were fitted with power-laws and subtracted from each annual spectrum. The average of the six annual power-law fits is indicated by the solid line in Fig. 1. The difference between the combined six-year spectrum and the SEP/CIR component is shown in Fig. 1 (upward triangular symbols) and represent the ACR oxygen component. This ACR O spectrum agrees well with that given by Mazur et al. (2000) and the slight discrepancies between the two spectra are easily understood as statistical in nature, arising from the different techniques employed (i.e., in Mazur et al., 2000, the SEP/CIR component of the spectrum is determined from the total six-year averaged spectrum, not individually from each of the six annual spectra). At and above 10 MeV/nucleon (downward triangular symbols), published, late-1995 ACR oxygen fluxes from the SAMPEX/HILT and SAMPEX/MAST sensors are shown (Mazur et al., 2000). In Fig. 1, as well as in Fig. 2a, where the published uncertainties were too small to detect, the estimated numerical precision in determining the value from the published figure is indicated by an error bar.

In Fig. 1 the annually averaged V1 (circular symbols) and V2 (square symbols) O spectra are from 1996 (this year was chosen since it is roughly in the middle of the 1993-1998 SAMPEX period, and is at a time when both inner and outer heliospheric ACRs are still in the recovery phase). These spectra are totally determined by ACR oxygen except possibly for the lowest energy V1 point at 0.3 MeV/nucleon.

The time-intensity profiles of inner and outer heliospheric low-energy ACR oxygen are shown in Fig. 2a. The 1-AU data (triangular symbols) are a combination of new SAMPEX/LICA observations and published ACE & WIND spacecraft data. The published data-points are 3-4 MeV/nucleon IP ACR oxygen data from the LEMT instrument on the WIND spacecraft with times centered on 1995.55 (Reames et al., 1997), 1995.61, and 1996.14 (Cummings et al., 1997) and ACE/ULEIS measurements of 2-4 MeV/nucleon IP ACR oxygen centered on 1997.95 (Christian et al., 1999). The five remaining data-points in Fig. 2a were calculated from the same SAMPEX/LICA data used to construct the 1-AU spectrum in Fig. 1. The 1.75- to

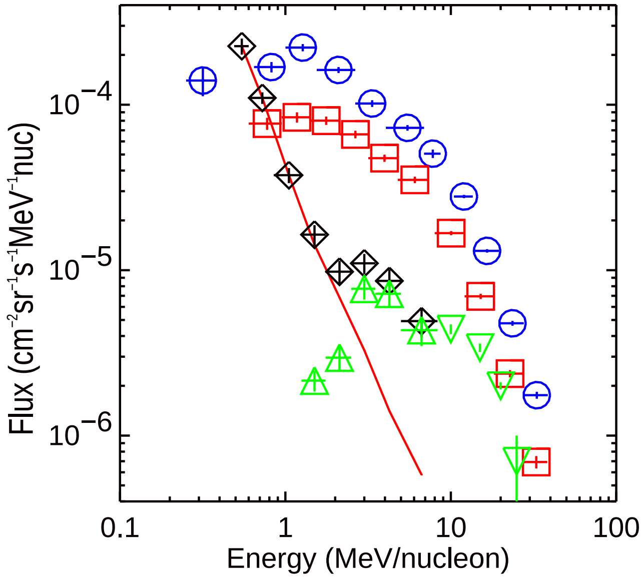

Fig. 1 Oxygen spectra from V1/LECP (circles) and V2/LECP (squares) during 1996. Interplanetary oxygen spectra from SAMPEX/LICA (diamonds), with an average of six annual power-law fits to the SEP/CIR components (solid line; see text), and the resulting ACR oxygen spectrum (upward triangles), all from 1993 to 1998. The ACR oxygen at and above 10 MeV/nucleon are from late-1995 SAMPEX/HILT,MAST data (downward triangles; Mazur et al., 2000).

5.00-MeV/nucleon ACR oxygen fluxes were determined from the 1993 to 1998 SEP/CIR-subtracted annual ACR oxygen spectra discussed above. The SAMPEX/LICA data-point from 1995 has been suppressed due to poor statistics.

The Voyager data shown in Fig. 2a are 26-day averaged ACR O measurements from the LECP instruments with V1 and V2 energy ranges of 1.00 to 4.05 MeV/nucleon and 0.94 to 4.78 MeV/nucleon, respectively. In Fig. 2b the time-intensity profiles for high-energy ACR oxygen are shown. For the 1-AU region, published SAMPEX/HILT, SAMPEX/MAST, and ACE/SIS measurements show 7- to 29-MeV/nucleon intensities versus time from the years 1992 to 2000 (Selesnick et al., 2000). For the outer heliosphere, again Voyager/LECP observations are presented, utilizing 26-day averages and energy ranges of 6.89 to 27.6 MeV/nucleon and 8.00 to 27.4 MeV/nucleon for V1 and V2, respectively.

3. Discussion

The energy spectra in Fig. 1 show the energy at the peak in the ACR oxygen spectra to be about 1.3 MeV/nucleon in the outer heliosphere as compared with a peak energy value of 3-4 MeV/nucleon at 1-AU. The V2 to SAMPEX intensity ratio is ~8 at 3 MeV/nucleon and ~2 at 20 MeV/nucleon. These observations are in qualitative agreement with the large-scale diffusion of ACRs from the outer to the inner heliosphere, with the lower-rigidity particles being more efficiently shielded from the inner heliosphere.

One of the striking features of the ACR O time histories at both low and high energies (Fig. 2a and 2b) is the large delay between the onset of renewed modulation at 1 AU and that in the outer heliosphere. For high-energy oxygen (Fig. 2b) there is no sign of significant large scale modulation at V1 or V2 until the second half of 2000, despite a rapid drop at 1-AU beginning in the second half of 1997. It should be noted that ACR O with an energy range of 13 to 38 MeV/nucleon at V1 and V2 (not shown) shows no sign of renewed modulation through the end of 2000. In the low-energy data (Fig. 1a), as in the high-energy data, the flux at 1-AU drops noticeably in 1997 and continues to do so in 1998, while the outer heliospheric low-energy anomalous oxygen does not decrease significantly until late 1999 or early 2000.

These facts indicate a modulation lag time of 2 to 3 years between the inner and outer heliosphere, despite the solar wind velocity propagation of solar disturbances that would be expected to result in significant modulation at the Voyager spacecraft within 160 to 300 days, using fast and slow solar wind speeds of 750 km/s and 400 km/s, respectively. Thus the observed lag is roughly three times longer than expected. This might suggest that the distant heliosphere is initially not very sensitive to the large-scale temporal, solar-cycle variations in modulation conditions so well observed at 1 AU. On the other hand, the outer heliosphere does appear to respond to some shorter term (~150 day) solar variations (Hill et al., 2001). The large, factor of ~10 increase in the V1 and V2 low-energy flux from 1994 to 2000 (Fig. 2a) might therefore be explainable by a significant spatial effect resulting from the spacecraft moving through a relatively stable spatial structure with a significant radial gradient. This view appears to require a substantial pile-up of disturbances in the IP medium before the outer heliospheric spatial structure is disrupted and eventually rapidly brought out of equilibrium, resulting in a comparatively sudden decrease such as is observed in the last half of 2000 (Fig. 2a). The continued modest modulation of high energy oxygen flux (Fig. 2b) and lack of modulation above 13 MeV/nucleon (not shown) could indicate that the ACR source flux is still relatively stable even as solar maximum approaches, and that the solar disturbances are still too weak as of 2000 to significantly impede the high-rigidity particles from gaining access to the outer heliosphere.

A comparison of inner and outer heliospheric low-energy ACR O intensities versus time (Fig. 2a), in light of both simple and sophisticated transport models also suggests that a large portion of the low-energy ACR increase is due to spatial rather than temporal effects. The simple observation that the rates of increase at V1 and V2 (both with rates of 15±6 %/year) are larger than the rate of increase at 1 AU (10±9 %/year) has potentially quite interesting implications (where the rates of increase were determined from exponential fits to the data during the period after the initial, rapid recovery, and before the onset of modulation – see Fig. 2 caption). Numerical solutions to the spherically-

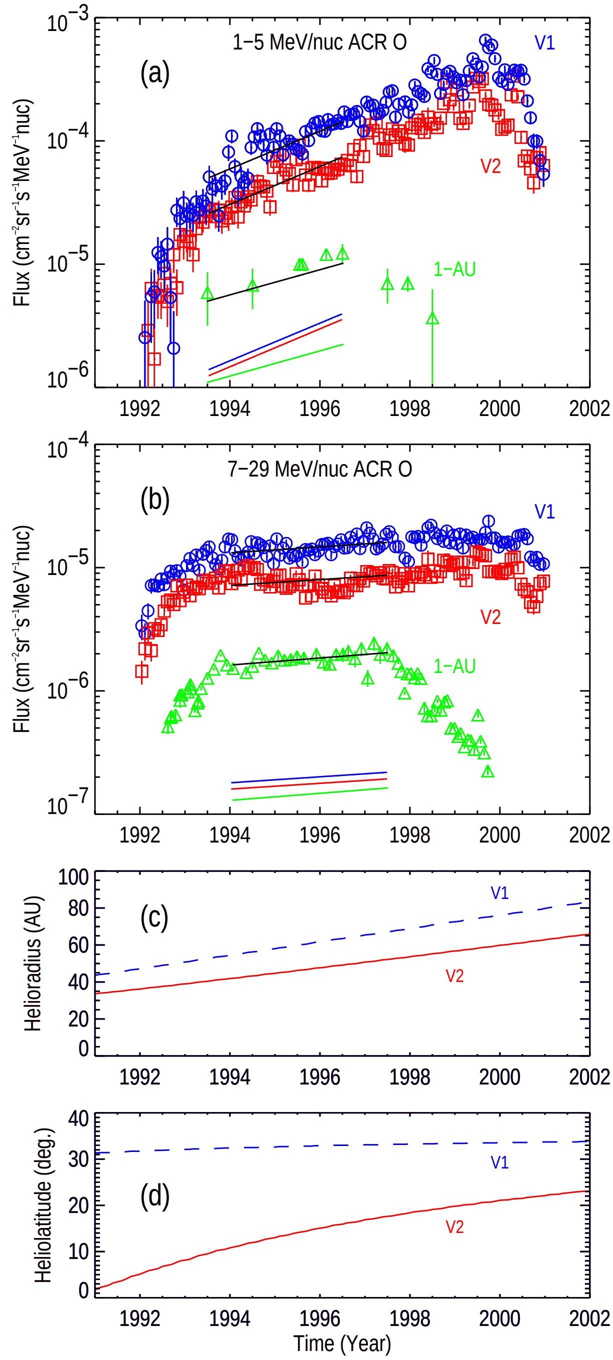

Fig. 2 Intensity versus time profiles of (a) 1- to 5-MeV/nucleon and (b) 7- to 29-MeV/nucleon ACR O from V1 (circles), V2 (squares), and SAMPEX, WIND & ACE (triangles). In panel (b) the SAMPEX & ACE data are from Selesnick et al., 2000. (c) Helioradii and (d) the absolute value of the heliolatitudes for the V1 (dashed line) and V2 (solid line) spacecraft, at northern and southern latitudes, respectively. The solid lines drawn through the data in panels (a) and (b) are segments of exponential fits (i.e., linear fits to the log of the flux) to the post-rapid-recovery / pre-modulation period, shown only where all three heliospheric regions are in this state. The three solid lines at the bottom of the two top panels are parallel to, and in the same order as the fit lines above, to facilitate comparison of the slopes.

symmetric convection-diffusion equation with a constant outer source show that observer-*A*, at large radii, near the source, would see an intensity that initially rapidly increases to a near time-asymptotic value and then gradually more closely approaches the asymptotic value during the remainder of the evolution of the system. For observer-*B*, further removed from the source at small radii, the rate of increase is initially much slower than for observer-*A* but is significantly greater than observer-*A* during observer-*A*'s later gradual asymptotic approach.

This behavior is also born out in a more sophisticated acceleration/modulation model of ACR H in the heliosphere (Steenberg and Moraal, 1996). This suggests either that (1) ACR O is evolving in a manner inconsistent with large scale diffusion from the outer to the inner heliosphere, or that (2) there is a significant non-temporal component in the increasing low-energy oxygen observed at the two Voyager spacecraft from 1994 to 2000 (Fig. 2a). The spectral evidence (Fig. 1) is in strong disagreement with possibility (1), and the most probable weak-diffusion model is a drift dominated heliosphere. However, the smaller than expected latitudinal gradients observed at Ulysses (e.g., McKibben, 1998) have already placed limits on the relative importance of drifts during the A > 0 period, at least at high latitudes, and easy access of ACRs over the solar poles is also not expected (Jokipii et al., 1995). This leaves possibility (2) as the more likely explanation. In particular, this supports the interpretation that the large low-energy increases seen at V1 and V2 after 1994 (Fig. 2a) are substantially governed by spatial effects.

For high-energy oxygen (Fig. 2b) the situation is reversed with the 1-AU data from 1994 to 1997 evidencing a slightly larger rate of increase (3±1 %/year) than observed in the outer heliosphere (2.4±0.4 and 2.4±0.5 %/year for V1 and V2, respectively). This is what would be expected from both the simple and sophisticated (Steenberg and Moraal, 1996) transport models, since at these energies, there is no sign of a large spatial gradient in the outer heliosphere (see e.g., Fig. 2b and Cummings et al., 1997) to prevent a primarily temporal interpretation of the high-energy time histories.

When the high- and low-energy ACRs (Fig. 2a and 2b) are compared to one another, however, the acceleration and transport model (Steenberg and Moraal, 1996) disagrees with the observations. This model, at a given location, predicts that the lower energy particles will approach the asymptotic values significantly earlier than do the higher-energy particles. This is physically reasonable in terms of the model, as the acceleration time for the higher-energy particles is longer than the acceleration time for the relatively easily accelerated low-energy particles. The data show that the rate of increase of the high-energy 1-AU ACRs is smaller than the rate of increase of the low-energy 1-AU ACRs. In the outer heliosphere, unless all of the post-1994 variation of low-energy ACR oxygen is due to a positive radial gradient, then the temporal variation of the low-energy ACRs at a fixed position is probably increasing at a rate faster than the high-energy ACRs. If spatial effects do dominate the low-energy increase then, in the extreme, the low-energy temporal increase at a fixed location could be the same as the high-energy ACR oxygen rate of increase, while ongoing acceleration at the TS would be expected to result in a faster long-term rate of change for the high-energy particles than for the low-energy particles. Thus the Voyager and 1-AU observations are not in agreement with significant continued acceleration at the termination shock after ~1994. In fact, all of these observations are explainable if one assumes that the TS source is nearly constant during most of the recovery period and that diffusive effects dominate the particle transport.

4. Summary

We have presented a comparison of the time histories and energy spectra of anomalous cosmic ray oxygen at low (1 to 5 MeV/nucleon) and high (7 to 29 MeV/nucleon) energies, in the inner (1 AU) and outer (36 to 80 AU) heliosphere. The spectra (Fig. 1) strongly support large scale diffusion of ACRs from the outer to the inner heliosphere and the rates of increase of the ACR oxygen time-intensity profiles (Fig. 2), along with the timing of the onset of renewed modulation in the inner and outer heliosphere, support diffusion dominated ACR transport and are consistent with a relatively constant source flux at the termination shock throughout most of the ACR recovery period. In addition the observations and the preceding interpretation are consistent with a largely spatial explanation for the large low-energy ACR oxygen increases seen at V1 and V2 from 1994 to 2000 (Fig. 2a).

Acknowledgements. This work was supported by NASA via Johns Hopkins University Applied Physics Laboratory subcontract 735138 to the University of Maryland and by an American Astronomical Society/NASA travel grant to MEH. This paper is from a dissertation to be submitted to the Graduate School, University of Maryland, by MEH in partial fulfillment of the requirements for the Ph.D. Degree in Physics.

References

Christian, E.R., et al., *Proc. 26th Internat. Cosmic Ray Conf.*, *7*, 519-522, 1999.

Cummings, A.C., et al., *Proc. 25th Internat. Cosmic Ray Con.f*, *2*, 257-260, 1997.

Hill, M.E., Hamilton, D.C., and Krimigis, S.M., *J. Geophys. Res.*, *106*, 8315-8322, 2001.

Jokipii, J.R., Kota, J., Giacalone, J., Horbury, T.S., and Smith, E.J., *Geophys. Res. Lett.*, *22*, 3385-3388, 1995.

Mazur, J.E., Mason, G.M., Blake, J.B., Klecker, B., Leske, R.A., Looper, M.D., and Mewaldt, R.A., *J. Geophys. Res.*, *105*, 21015-21023, 2000.

McKibben, R.B., *Space Sci. Rev.*, *83*, 21-32, 1998.

Reames, D.V., Barbier, L.M., and von Rosenvinge, T.T., *Adv. Space Res.*, *19*, 809, 1997.

Selesnick, R.S., Cummings, A.C., Leske, R.A., Mewaldt, R.A., Stone, E.C., and Cummings, J.R., *Geophys. Res. Lett.*, *27*, 2349-2352, 2000.

Steenberg, C.D. and Moraal, H., *Astrophys. J.*, *463*, 776-783, 1996.