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Heliospheric interactions with Kuiper Belt Objects

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Abstract. Interactions of heliospheric plasma, energetic particles, and dust with icy surfaces of Kuiper Belt Objects (KBO) in the outer heliosphere have potentially observable effects on surface chemistry of these objects. Although most detected KBO's have circular orbits at 30-50 A.U. within the heliosphere, some of the Centaur and Scattered Kuiper Belt Objects (SKBO) have sufficiently eccentric orbits to pass through the solar wind termination shock (~ 80 – 120 AU) into the heliosheath region. Within this boundary region the primary radiolytic energy source may be anomalous cosmic ray ions accelerated at the shock. A few SKBO's have aphelia . 10^3 A.U. and are periodically exposed to unmodulated galactic cosmic ray irradiation in the very local interstellar medium (VLISM). Time scales for significant radiolytic evolution of surface ices to sensible depths of microns to cm's are the Solar System age for KBO's far inside the termination shock, 10^3 - 10^6 years in the heliosheath, and 10^6 to 10^9 years in the VLISM.

1 Introduction

In Figure 1 we show orbital parameters for two comet populations with significant eccentricities in the outer solar system beyond Jupiter's orbit. Centaurs are minor planets with semi-major axes between orbits of Jupiter and Neptune. These objects are thought to originate beyond the orbit of Neptune in the Kuiper Belt at 35 – 1000 AU. Dynamical lifetimes of Centaurs are 10^6 to 10^7 years due to strong orbital perturbations by the two large planets, making them candidates for population of the Oort Cloud at 20,000 – 100,000 AU, and many have large eccentricity. Scattered Kuiper Belt Objects (SKBO) have moderately inclined orbits and high eccentricity with perihelia in a small range 34 AU < q < 36 AU near Neptune's orbit, suggestive (Trujillo et al., 2000) of an origin from scattering by that planet. The SKBO population is defined by semi-major axes beyond the 41 < a < 46 AU range of the classical KBO's (Jewitt and Luu, 1993; Jewitt et al., 1996; Jewitt, 1999). The latter number about 2/3 of all known KBO's, while resonant KBO's are found at the 39.4 AU location of near the 3:2 orbital resonance with Neptune.

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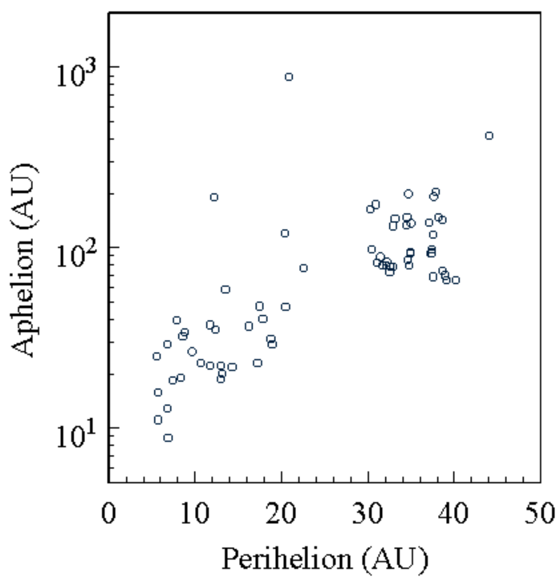

Figure 1. Radial limits of heliocentric orbits for Centaurs and Scattered Kuiper Belt Objects (Minor Planet Center, Harvard University, May 2001).

The more eccentric of the Centaurs and SKBO's very likely traverse the solar wind termination shock located somewhere beyond the 82 AU present distance of our most distant spacecraft, Voyager 1. A few completely pass through the heliosheath, bounded by the heliopause at ~ 150 – 200 AU, into the very local interstellar medium (VLISM) out to 1000 AU. As such, these objects could be natural probes of the space radiation environment in the heliospheric boundary regions and beyond, if astronomical observations near perihelia would reveal details of surface composition that might be related to irradiation effects. Present knowledge of SKBO composition is very limited.

Within the heliosphere, comets are fully irradiated by GCR ions and electrons to meter depths over the age of the Solar System (Johnson et al., 1987). The GCR are heavily modulated in spectral intensity below one GeV/nucleon within the heliosheath. Cooper et al. (1998) first proposed that comets might experience chemically significant irradiation in the outer heliosphere from anomalous cosmic ray (ACR) ions accelerated at the termination shock. In comparison to modulated GCR, the ACR ions peak in intensity below 100 MeV/nucleon, as do the unmodulated GCR spectra in the VLISM, so energy fluxes of the ACR and VLISM GCR ions are mostly deposited within microns to centimeters of the outermost surface on the irradiated objects. This is the depth range accessible to remote sensing observations at UV to IR wavelengths.

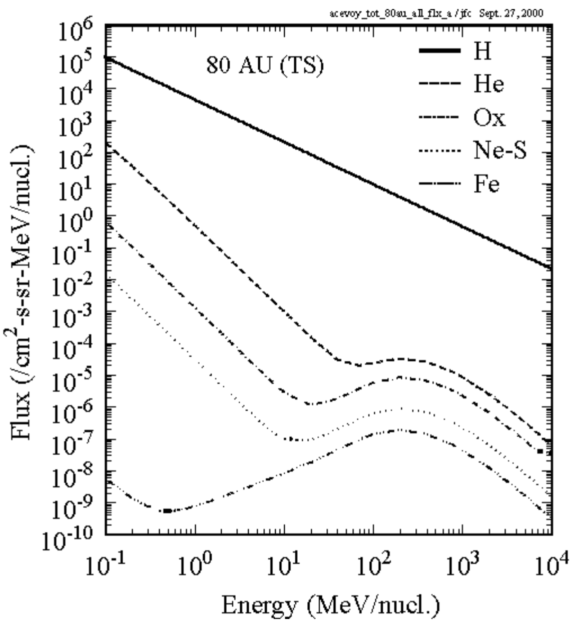

Figure 2. Summed flux spectra at 80 AU of ACR ions from local acceleration by solar wind termination shock and of heliosheath-modulated GCR ions from the VLISM source spectra in Figure 3.

A Centaur could traverse the outer heliosphere 10^3 – 10^5 times before scattering by Jupiter or Neptune, and residence times for SKBO's would be longer. Integral dosage fluence would depend on total residence times and on fractions of orbital time spent in regions of more intense fluxes near and beyond the termination shock. Since large fractions of time in highly eccentric orbits are spent near aphelion, an object with an aphelion near the time-averaged position of the termination shock might accumulate the greatest irradiation level.

2 Semi-Empirical Flux Model for GCR and ACR Ions

A cosmic ray flux model, derived from earlier work of Stone et al. (1996) and Cooper et al. (1998), has been implemented to provide differential flux spectra for galactic, anomalous, and solar cosmic ray ions in five element groups: H, He, CNO, Ne - S, and Fe. In the heliosphere, all three populations vary greatly over 11-year sunspot cycles and the 22-year magnetic cycle. At 1 AU the GCR spectra are compiled from long term average intensities measured for three years from Sept. 1997 during solar quiet intervals by the Cosmic Ray Isotope Spectrometer onboard the Advanced Composition Explorer (ACE) spacecraft. In this report we ignore the solar fluxes.

In the outer heliosphere the GCR spectra were acquired out to 79 AU by the Cosmic Ray experiments on the Voyager 1 and 2 spacecraft. GCR spectra for each element group were computed at selected heliocentric radii (1, 5, 40, and 80 AU) from fits of the peak GCR intensities at

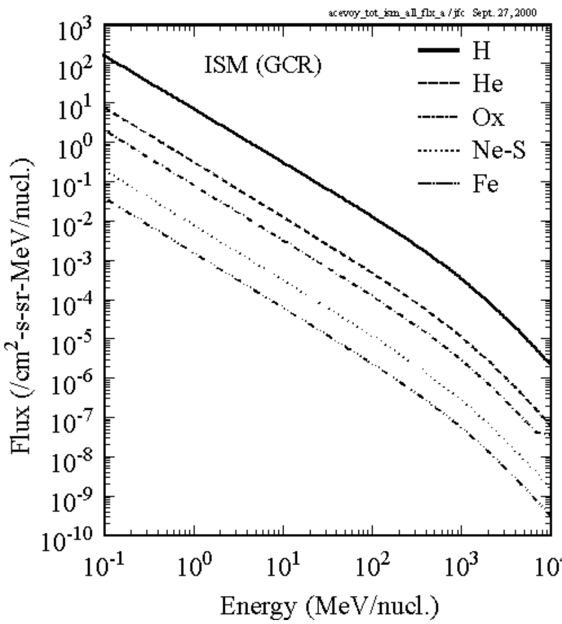

Figure 3. Model for demodulated flux spectra of GCR ions in the VLISM radiation environment.

ACE and the Voyagers for a 1-D solar modulation model and a VLISM model for demodulated GCR ion spectra (Figure 2) in these groups. The ACR components were computed similarly for an assumed shock spectrum at 80 AU (Stone et al., 1996) and modulation model parameters determined from fits to ACE and Voyager peak intensities. Our semi-empirical model spectra for the VLISM and 80 AU are shown respectively in Figure 2 and 3.

3 Radiolytic Dosage Model

Significant chemical change is induced at the molecular level in mixed ices in which about 100 eV is deposited per molecule (standard mass unit = 16 amu) via electronic ionization of the target material by incident charged particles (Johnson, 1990; Strazzula et al., 1991). In Figures 4 and 5 we show the times needed in years to accumulate such dosages at visible surface depths down to one centimeter in water ice (unit density) as the result of irradiation by the respective flux spectra in Figures 2 and 3. The dosages are computed by numerical methods described in Cooper et al. (2001). Only electronic ionization by primary ions is included; there are no dosages from secondary products of nuclear and electromagnetic interactions. Near the assumed termination shock these times are extremely short at 10^3 to 10^6 years, the micron layers being fully processed over several orbit periods for objects with aphelia near the shock position. In the VLISM the dosage times range from 10^6 years at micron depths to classical KBO values (see below) of 10^9 years lower down.

For example, the SKBO object 1999 DE9 spends 27% of its 416-year orbital period within 5 AU of its aphelion at 79 AU, close to the assumed shock although Voyager data tell us it must be further out. The more eccentric object 1996 TL66 (Luu et al., 1997) passes far beyond the shock to 140 AU and is within 5 AU of our assumed shock only six percent of its 784-year period. If the shock flux is constant within that 5-AU interval, however, the dose accumulation time is still only ~ 10^4 years at micron depths and ~ 10^7 years at limiting depths for spectroscopic analysis.

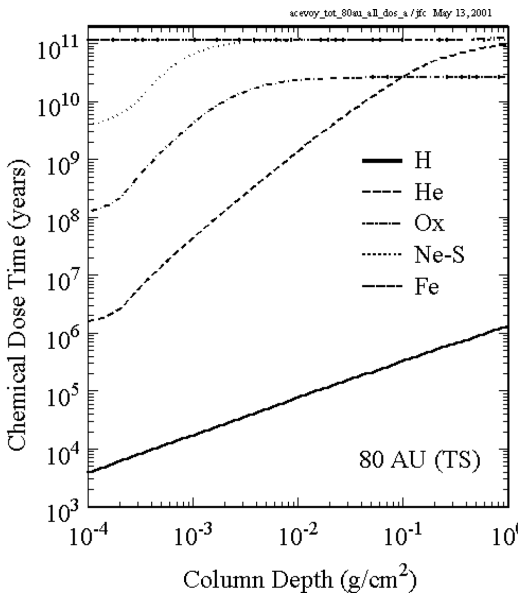

Figure 4. Depth profiles for times in years to accumulate 100-eV/16-amu in dosages from flux spectra in Fig. 2 for significant radiolytic processing of comet ices at 80 AU.

For the flux spectra and associated irradiation at 1, 5, and 40 AU, the dosage times for 100-eV/16-amu from electronic ionization by the primary ions are negligible compared to dosages from secondary interaction products. To recheck these times for applicability to the classical and resonant KBO's far inwards from the termination shock, we assume a constant level of GCR intensity at 1 – 40 AU and use the CREME96 model (Tylka et al., 1997) for GCR ion spectra during average solar modulation conditions at 1 AU. Even without SEP contributions the resultant dosage time is ~ $2x10^9$ years. Secondary dosages will be directly computed with radiation transport codes for all locations in the future.

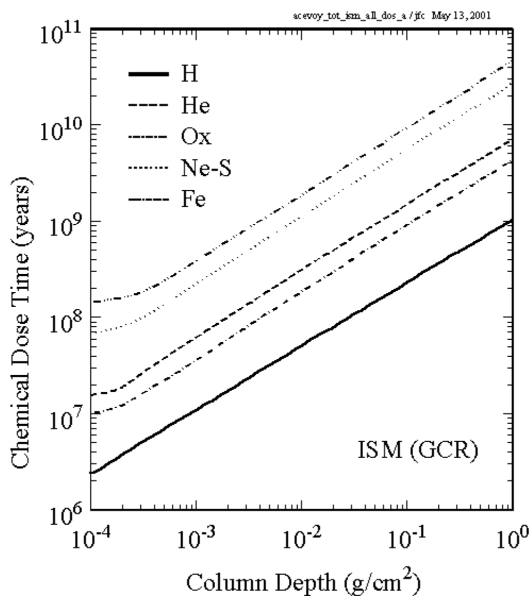

Figure 5. Radiolytic dose times for comets in the VLISM irradiation environment from demodulated GCR ion spectra in Fig. 3.

4 Discussion

Our results for the 80-AU case assume that the model spectrum at the termination extends at constant intensity within 5 AU of the shock. At the time of this writing we had not yet completed a model of ACR ion intensity as a function of distance from the shock. This should be available by the time of presentation at the conference.

If the region of peak flux were more like the gyroradii ~ 0.1 AU of 100 MeV protons at 80 AU in a 0.1-nT interplanetary magnetic field, this would reduce the time-averaged irradiation flux on objects passing through this region by about two orders of magnitude. The 80-AU irradiation time scales at µm – cm depths would then be 10^5 – 10^8 years, still more than in the VLISM. An interesting consequence is that within the peak flux region the radiation dosage rate would be about 50 rad per month at 1-cm depth, so any natural or man-made object moving through this region outward at 10 AU per year would get a cumulative dose of six rad.

If the actual shock is located further out, say at 100 AU, this would not affect irradiation of more eccentric objects like 1996 TL66 but could substantially change irradiation levels for objects closer or farther from the actual position. Objects having aphelia near the shock position will experience the greatest levels of irradiation, but this position may actually move tens of AU in response to solar cycle changes in solar wind parameters, so the 1996 TL66 case may be more applicable.

The available spectroscopic observations on KBO's, mostly those with aphelia . 50 AU, show a range of surface compositions from reddened spectra characteristic of volatile-depleted irradiation mantles (Johnson et al., 1987) to more neutral spectra associated with surface covering by dust from the object interiors. The color spectrum of the SKBO 1996 TL66 is very flat, while that of the Centaur 5145 Pholus is strongly reddened (e.g., Jewitt, 1999). Within the Centaur and various KBO populations there is diversity of color spectra (Luu and Jewitt, 1996; Barucci et al., 1999; Davies et al., 2000) within each of the distinct types with little or no ordering by orbital parameters. The commonality of color distributions among all object classes is attributed to common origins from the main Kuiper Belt. Tegler and Romanishin (2000) did find evidence for spectral bimodality and redder objects in near-circular, low-inclination orbits beyond 40 AU, but this not confirmed by Davies et al. (2000) using a larger sample of objects.

Luu and Jewitt (1996) first proposed that the observed color diversity might be explained by a combination of effects from cosmic ray irradiation and surface activity from impacts by other objects. They cited a collision time for more abundant km-size objects on 100-km KBO's of $10^6 – 10^8$ years. Durda and Stern (2000) modeled collision rates in the Centaur and Kuiper Belt regions, finding longer time scales of $7x10^7 – 4x10^8$ years for such impacts. While irradiation over $10^7 – 10^9$ years was presumed to deplete volatiles and redden the mixed ice surfaces, impacts and resultant redeposited ejecta could disrupt or cover the irradiation mantles on similar time scales. Thus the color diversity was accounted for by the statistics of collisions versus the steady rates of irradiation. New findings include the discovery of water ice on the otherwise color neutral Centaur 2060 Chiron (Luu et al., 2000) and time variations of spectra on the reddened Centaur 8405 Asbolus (Kern et al., 2000), consistent with patches of water ice on the rotating surface of the latter.

Improved understanding of the color diversity question for all Centaurs and KBO's, and for SKBO's at perihelia in particular, awaits a larger sample of spectroscopic observations. If the solar wind termination shock were stationary, we might expect enhanced irradiation mantle development and reddening for SKBO's with aphelia near the shock position. The shock may move substantially in response to solar wind variations, but other effects such as pressure from VLISM pickup and ACR ions might give rise to more stability in position while also radially thickening the shock zone and thus the region of peak flux.

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