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Oxygen in the heliosphere

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Abstract. Oxygen within the heliosphere, whether neutral or ionized, comes from both the external source in the local interstellar medium (LISM) and internal sources. If transient cometary sources are neglected, Jupiter is the strongest of the internal sources by virtue of its corotation and charge exchange driven neutral wind. O^+ pickup ions are born where the penetrating neutrals lose an electron as a result of photoionization, charge exchange with solar wind protons, or solar wind electron impact ionization. The region of the heliosphere from which these pickup ions arise depends on the phase of the solar cycle as well as on the velocities of the neutrals. The present model of neutral O populations and their ionization suggests that Jovian pickup ions can dominate the inner heliospheric O^+ population if the LISM neutrals are strongly filtered at the heliopause, or are excluded by strong ionizing fluxes from the Sun. Other heliospheric species such as sulfur and nitrogen may have similar origins. These planetary sources need to be taken into account in the interpretation of interplanetary gas and ion composition observations.

Introduction

The intriguing problem of the penetration into the heliosphere of the neutral local interstellar gas and its subsequent fate has been the subject of several decades of effort [e.g., *Axford et al.*, 1963; *Fahr*, 1968; *Holzer*, 1972; *Vasilyunas and Siscoe*, 1976; *Holzer*, 1989; *Fahr and Fichtner*, 1991]. Ulysses spacecraft results are now showing clear evidence of picked up hydrogen ions from this penetrating gas near the orbit of Jupiter [*Gloeckler et al.*, 1993], while observations of picked up interstellar helium ions have been available since the mid-1980s [*Mobius et al.*, 1985]. These newer in situ data, combined with the longer-standing remote sensing data from resonant solar Lyman alpha and 584-Å EUV photon scattering by the local hydrogen and helium clouds [e.g., *Bertaux and Blamont*, 1971; *Weller and Meier,* 1981; *Ajello et al.*, 1990; *Lallement et al.*, 1993], and the measurements of the anomalous cosmic ray (ACR) component with its likely origin in accelerated pickup ions [*Fisk et al.*, 1974; *Mewaldt et al.*, 1993] provide our key to what lies just beyond the solar system. At the same time, in connection with a diverse set of planetary and cometary observations and models (e.g., review by *Gombosi* [1991] and *Mendillo et al.* [1990]), together with developmental efforts related to "neutral particle" imaging techniques [e.g., *Williams et al.*, 1992] we have come to appreciate the nature and magnitudes of sources of both neutrals and pickup ions internal to the heliosphere. Even the Moon seems to be a detectable supplier of heliospheric ions [*Hilchenbach et al.*, 1992]. This convergence of results and the imminent spacecraft measurements from both Ulysses at high heliolatitudes, and probes such as Wind and ACE (Advanced Composition Explorer) that are yet to be launched, make it timely to ask questions about the relative contributions of these various sources to the heliosphere and their detectability. In particular, while the interpretation of the source of the observed hydrogen and helium as interstellar seems fairly unambiguous, the source of heavier elements with high first ionization potentials such as oxygen merits a second glance.

There has been only limited study of oxygen in the heliosphere. On the theoretical side, *Bleszynski* [1987], *Rucinski* [1992], and *Fahr* [1991] have made estimates concerning the likely abundance and heliospheric access of interstellar oxygen. On the experimental side, *Geiss et al.* [1992] reported on a search for low charge state oxygen ions using the Ulysses solar wind ion composition (SWICS) experiment. Those observational results, based on 6 days of measurements obtained between 1.3 and 1.4 AU heliocentric distance, gave an upper limit for the amount of picked up O^+ present at the spacecraft. New results showing the O^+ radial gradient have just recently been released [*Geiss et al.*, 1994]. Here we describe a calculation of some of the basic features of the heliospheric oxygen population that might be expected based on current knowledge, including consideration of the internally supplied component. We compare interstellar and planetary sources for solar minimum and maximum conditions but neglect the dust, meteoric, and transient cometary contributions. The results suggest where oxygen populations, both neutral and ionized, of planetary origin could dominate and thus provide a theoretical framework for observational analyses.

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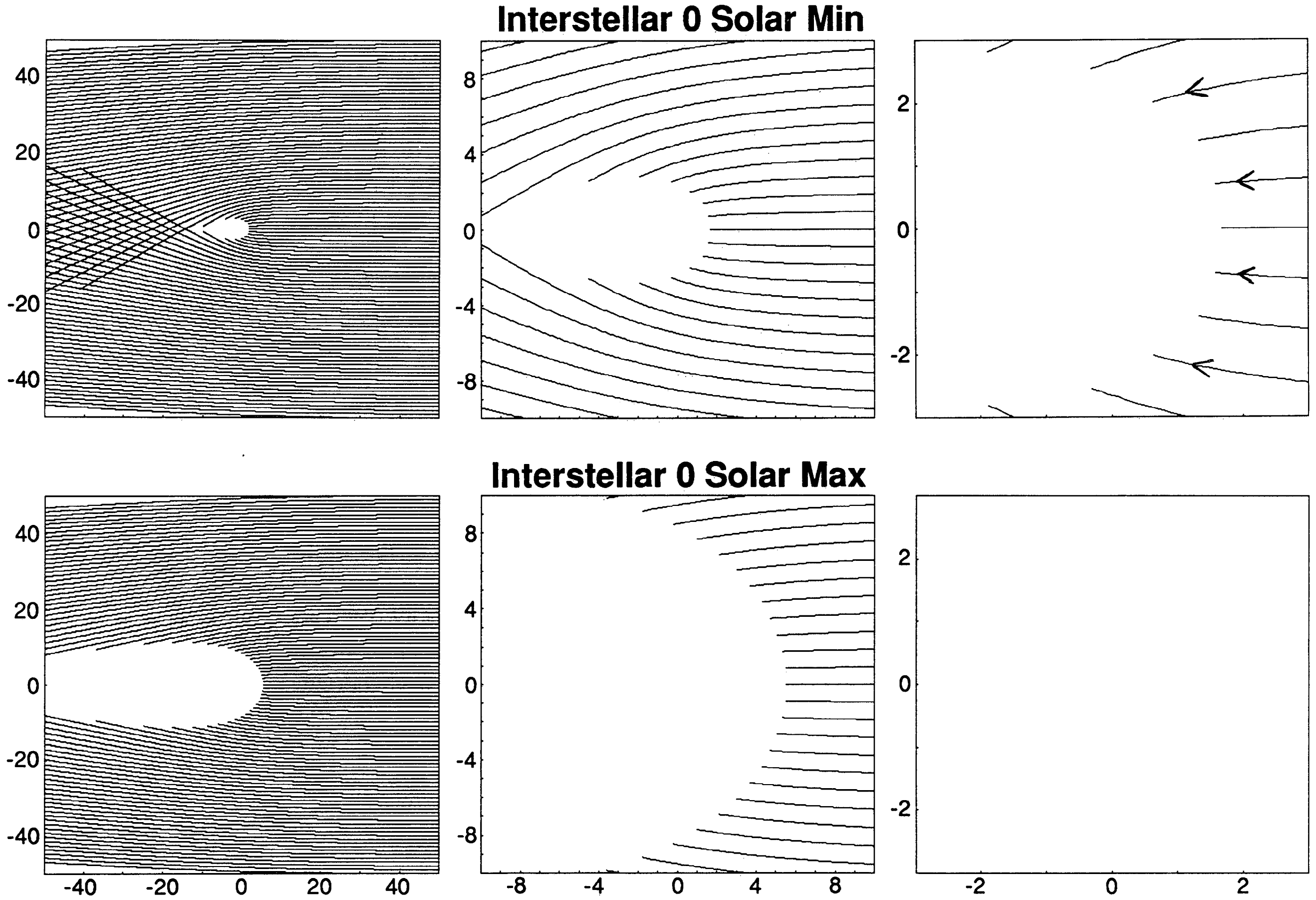

Figure 1. Interstellar neutral O atom trajectories originating at 50 AU, shown on three scales each for solar minimum and solar maximum. The plane containing these trajectories passes through the Sun at the origin. The trajectories are uniformly spaced and the particles enter the heliosphere at 20 km s^{-1}, moving toward the left. The scales are AU from the Sun. Solar gravity causes the trajectories to focus near the Sun. The trajectories are terminated where ionization occurs. If the interstellar source is uniform, this configuration of trajectories is cylindrically symmetric with respect to the inflow axis through the Sun.

Neutral Oxygen Sources

Neutral (atomic) oxygen O enters the heliosphere from both the external interstellar gas source and internal planetary, cometary, dust, and meteoric sources. The access of the interstellar component has been discussed in some detail by *Rucinski* [1992] and *Fahr* [1991]. In general, it is considered that O is present in the interstellar gas at the cosmic abundance of $\sim 6.76 \times 10^{-4}$ relative to hydrogen [e.g., *Cameron*, 1973]. Recent analyses of the Lyman alpha background data give local interstellar hydrogen densities between ~ 0.05 and ~ 0.2 cm^{-3} [*Lallement et al.*, 1993], while *Gloeckler et al.*'s [1993] in situ Ulysses results indicate that the value ~ 0.1 cm^{-3} can produce the observed population of hydrogen pickup ions. With these numbers, one can estimate that the flux of interstellar oxygen in the local interstellar medium (LISM), flowing at ~ 20 km/s relative to the Sun [e.g., *Axford*, 1972], is ~ 150 $cm^{-2}s^{-1}$. The order of ~ 30% of these atoms may be ionized and thus deflected around the heliopause according to *Fahr* [1991]. There is considerable uncertainty concerning the importance of a "filtering" effect at the heliopause boundary that also excludes some of the incident neutrals [e.g., *Bleszynski*, 1987; *Rucinski*, 1992; *Fahr*, 1991]. *Fahr* [1991] suggests a transmissivity of 10%, but 100% transmission cannot be ruled out on the basis of current knowledge. Although these factors reduce the entering interstellar O flux to $\sim$10-100 $cm^{-2}s^{-1}$, the large cross section of the heliosphere $\sim \pi R_h^2 \approx \pi(50 \text{ to } 100 \text{ AU})^2$ makes the number of entering O atoms $\sim 10^{31}$ to $10^{33}s^{-1}$. This number can be compared with the strengths of the internal sources.

Planets can be sources of interplanetary O if processes in their atmospheres or magnetospheres can produce O above the escape velocity for the planet. According to *Barbosa et al.* [1984], *Eviatar and Barbosa* [1984], and *Barbosa and*

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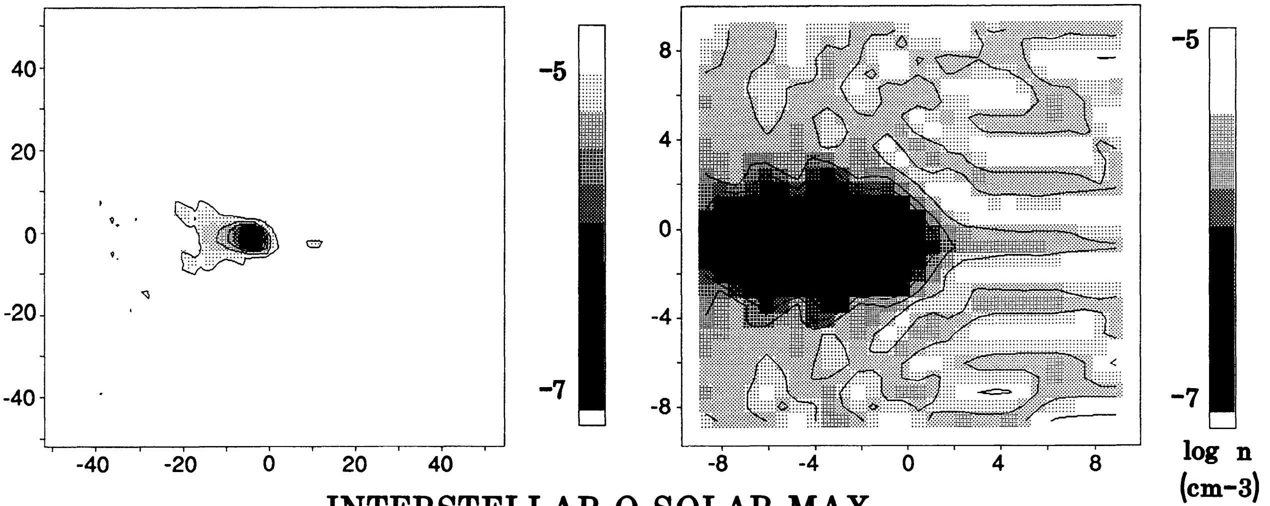

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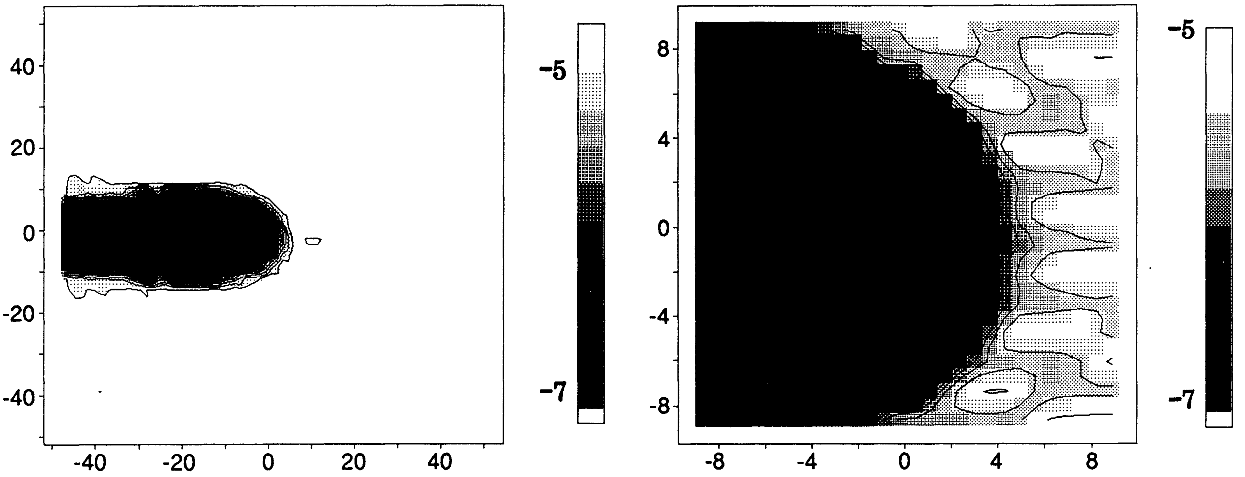

Figure 2. Contours of interstellar O densities based on the trajectories in Figure 1. Only the large (± 50 AU) and midscale (± 10 AU) perspectives are shown here. The graininess in the contours is an artifact of the manner in which the trajectory data are binned in 2 and 0.67 AU square spaces respectively.

Eviatar [1984], Jupiter produces $\sim$1-5x10^{28} s^{-1} escaping O atoms from a restricted latitude range near the Jovian equatorial plane. These atoms come from the charge exchange between Io torus neutrals and the torus O^+ ions that are accelerated to the $\sim$75 km s^{-1} corotation speed in Jupiter's rapidly rotating dipole magnetic field. Saturn's Dione-Tethys torus is considered another possible source of ($\sim$50 km/s) O that escapes into space by virtue of the corotation/charge exchange cycle, but *Barbosa and Eviatar* [1984] estimate that source strength at $\leq 10^{26}$ s^{-1}. Neptune and Uranus, while less well understood, do not appear to have the dense satellite tori observed at Jupiter and Saturn. The sporadic contribution of O from charge exchange of the O^+ in the storm time ring current in the Earth's hydrogen exosphere should be less ($\leq$30%) than the corresponding H loss of $\sim$ 5x$10^{25}s^{-1}$ [*Barbosa et al.*, 1984] if composition measurements are any indication [*Gloeckler et al.*, 1985]. Additional O escape from the ring current O^+ precipitation-induced sputtering of the upper atmosphere O is also expected to be $\leq 10^{25}s^{-1}$ [*Torr et al.*, 1974]. Other relatively weak sources are Mars and Venus, which respectively produce $\geq$ 5 km s^{-1} and $\geq$ 11 km s^{-1} O outflows of $\sim 10^{24}$- 10^{26} atoms/s from the dissociative recombination of ionospheric O_2^+ (in the case of Mars) [*Nagy and Cravens*, 1988] and/or sputtering by pickup ions reentering the atmosphere [*Luhmann and Kozyra,* 1991]. Thus Jupiter appears to be the largest planetary source of O.

Comets can produce O atoms when the water molecules that outgas at increasing rates as the comet approaches the sun photodissociate. The outgassing rates of comets can reach $\sim 10^{31}$ s^{-1} for a strong Halley-like comet near perihelion (for comparison, Comet Giacobini-Zinner's perihelion gas production rate was estimated at $\sim 10^{28}s^{-1}$, similar to the O source strength of Jupiter) [e.g., *Boice et*

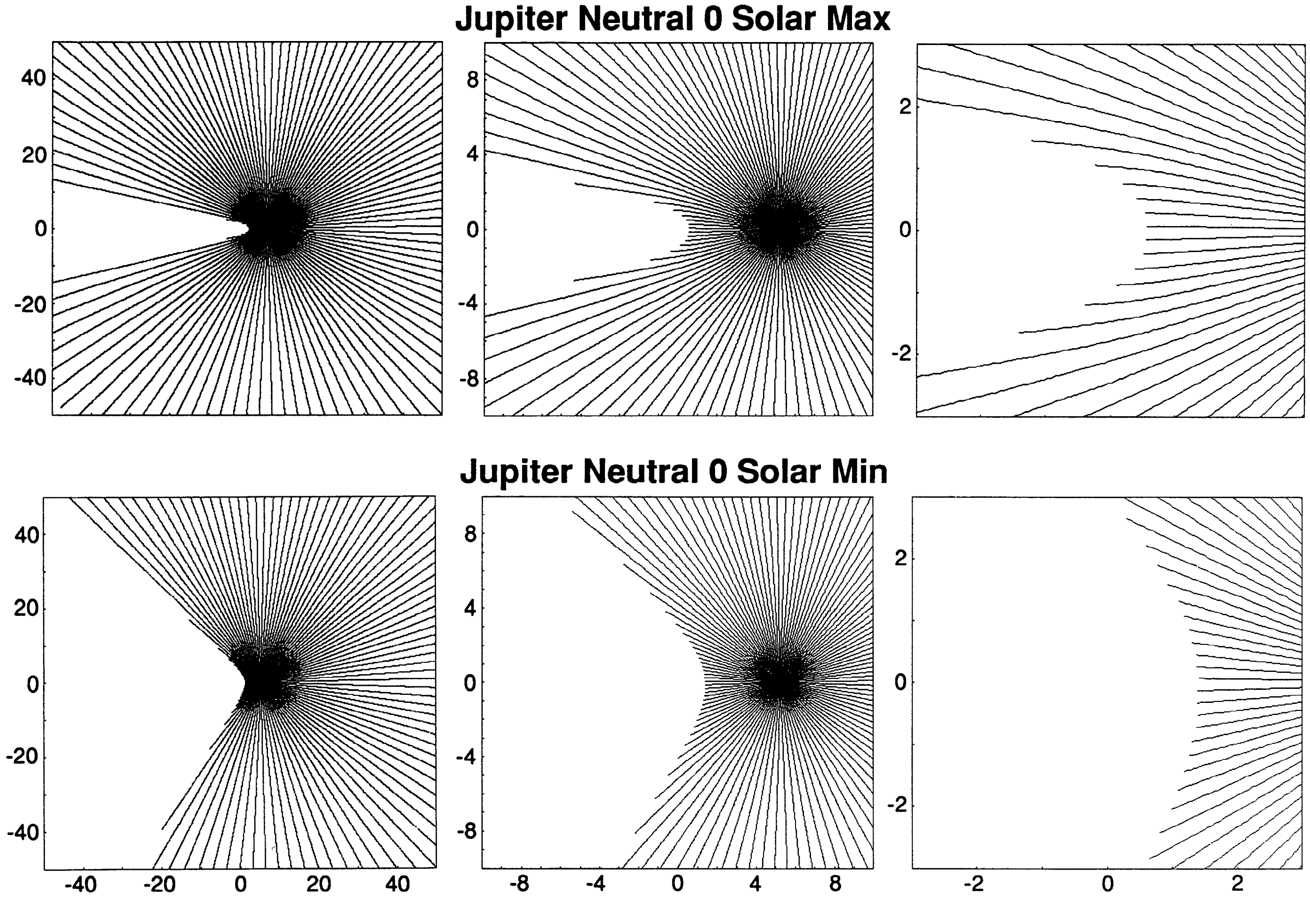

Figure 3. Same as Figure 1 but for neutral O of Jovian origin. Jupiter is presumed to be located at +5.2 AU on the abscissa. The view is for the Jovian equatorial plane which is presumed to be the source of the particles. The particles radiate from Jupiter at 75 km s^{-1}.

al., 1986]. If one assumes that all of the outgassed water eventually photodissociates, then strong comets would seem to represent a much greater source of heliospheric O than the planetary source. However, these sources are transient (their strength falls off rapidly with distance from the Sun) and likely to be limited in extent due to the relatively low (~1 km/s) outgassing velocity. For example, near 1 AU, O atoms emitted due to outgassing from the nucleus would travel only ~ 0.01 AU before being photoionized. Comet Halley was outgassing at near its perihelion rate while it was inside the orbit of Earth for only about 3 months between the end of 1985 and early 1986. It will not contribute at this rate again for ~ 76 years. (However, it is noteworthy that as far as gas production is concerned, Halley's case amounts to a respectable orbital average of ~$10^{28}s^{-1}$.) Of course, there are weaker and more frequent cometary sources passing through the heliosphere with various perihelion distances at any given time whose average production is undetermined. Perhaps more important from the viewpoint of the present study is the possibility that a minor population of ~10^{27}-10^{28} O atoms s^{-1} could be isotropically emitted from a Halley strength comet at 1 AU at the much higher velocities of ~40-60 km s^{-1}. This population can be generated when cometary pickup ions in the outer coma charge exchange with the neutrals and then collisionally thermalize in the inner coma [see *Ip*, 1990]. Nevertheless, on the basis of frequency with which a major comet like Halley appears, we here consider that comets generally represent temporally and spatially localized sources whose effects are confined to fairly short time intervals separated by much longer intervals. They contrast to the more "permanent" planetary oxygen sources, which will be emphasized here because of that permanence.

Two other possible internal sources are the particulate or meteoric source that has been proposed as a contributor of iron and silicon ions in the solar wind [e.g., *Lemaire*, 1990], and the desorption of accumulated gas from interplanetary dust grains [*Fahr et al.*, 1981]. As *Lemaire* [1990] has noted, the evaporation of grains and small bodies approaching the Sun should effectively add heavy elements to the solar wind, and the CNO family makes a small contribution to the composition of present-day meteorites. However, since this evaporation process occurs close to the Sun, in the course of infall, the evaporation products are

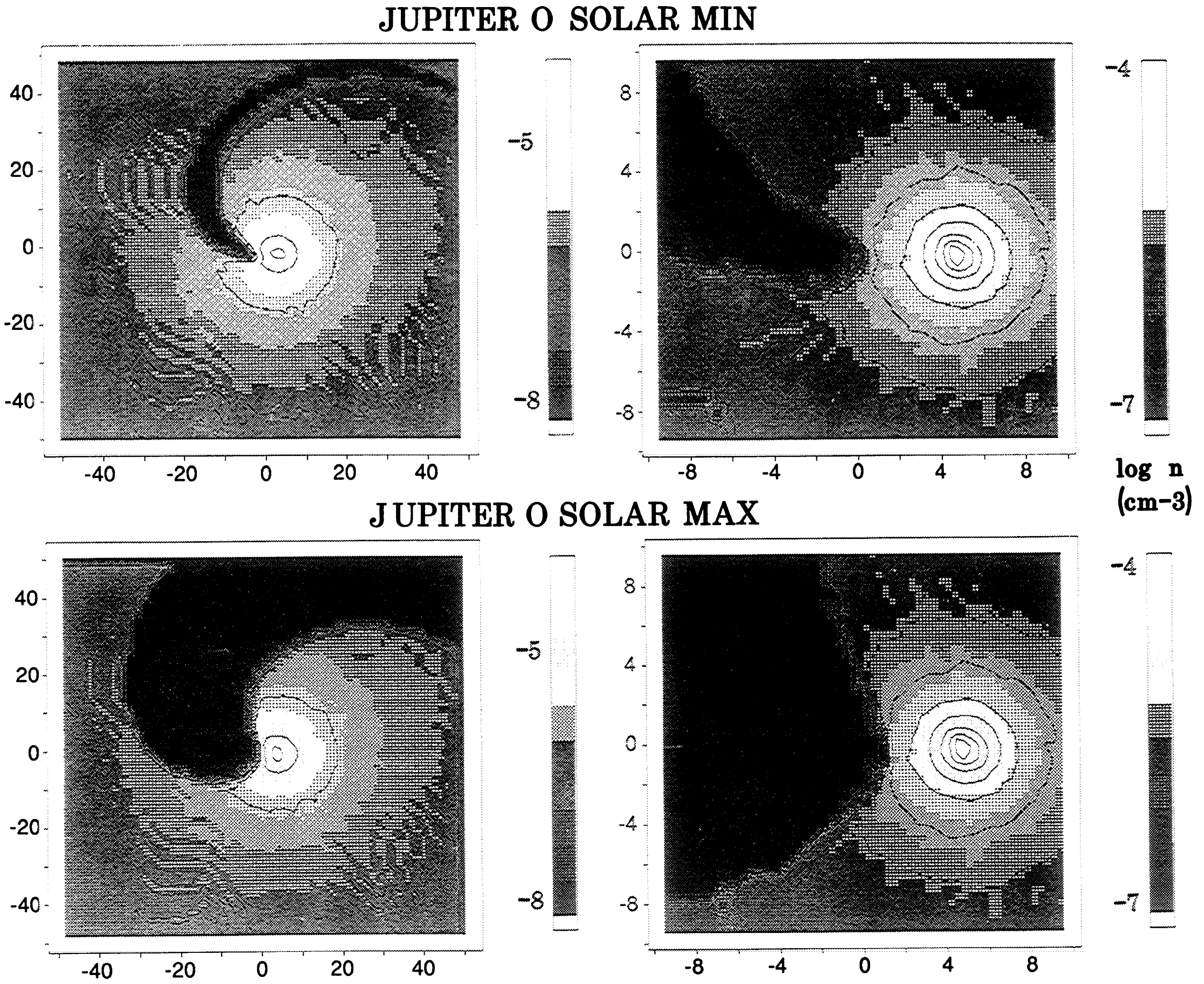
JUPITER O SOLAR MIN

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Figure 4. Same as Figure 2 but for the Jovian O densities. The density scale in this case was determined by presuming a divergence of the particles from the Jovian equatorial plane at the estimated thermal velocity for this source of ~13 km s^{-1}, and adjusting the density at 1 AU to that value. Thus densities closer to Jupiter are underestimated while those further away are over estimated.

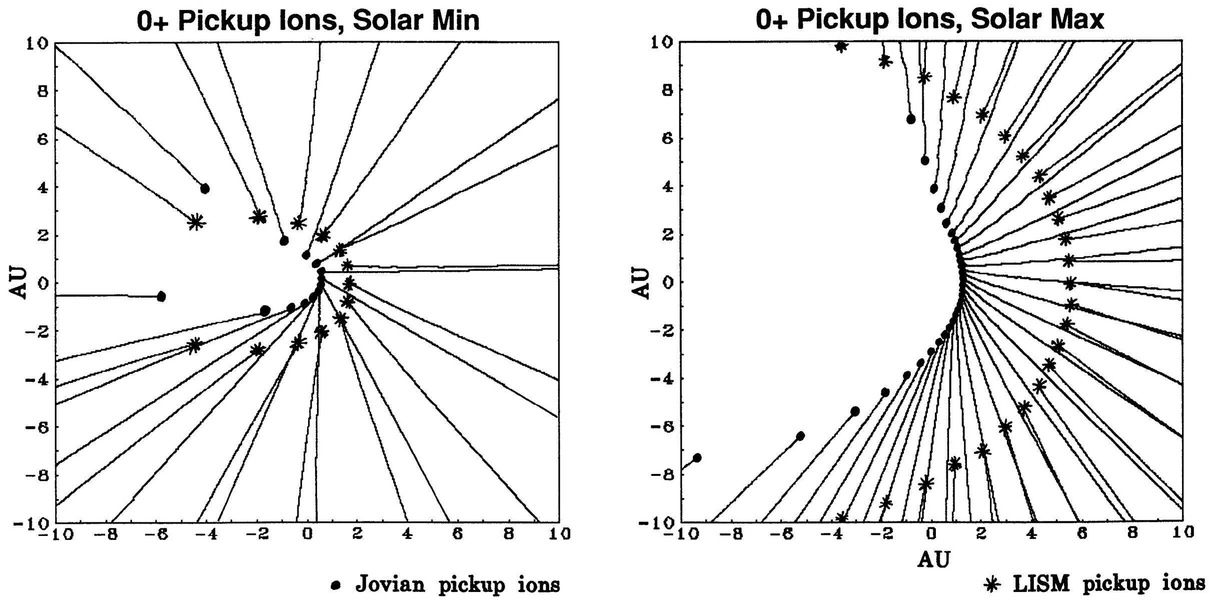
0+ Pickup Ions, Solar Min

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Figure 5. Trajectories of O$^+$ pickup ions at ±10 AU from the Sun. The ions of LISM origin (asterisks) were launched where the neutral trajectories in Figure 1 end; the ions of Jovian origin were launched at the ends of the trajectories in Figure 3.

likely to become highly ionized and accelerated by coronal acceleration processes like Coulomb drag. The dust-related neutral density similarly has a maximum close to the Sun (at ~0.02 AU according to the *Fahr et al.* [1981] model). The fate associated with deep penetration into the corona puts the potential meteoric and dust sources into a different category, more akin to that of solar wind minor ions. We thus also neglect these oxygen sources in the remainder of the present analysis.

The spatial distribution of the neutrals can be estimated by considering the various ionization processes that occur along an atom's trajectory through the heliosphere. The primary ionization processes affecting O atoms are photoionization, charge exchange with solar wind protons and impact ionization by solar wind electrons [e.g., *Fahr*, 1990]. Usually, a single ionization is assumed, although there may be limited circumstances under which a second electron could be removed. Taking the above ionization processes into account, together with solar gravity, one can track the O atoms from their source(s) and determine approximately which ones are ionized and where. While this test particle technique cannot easily simulate some of the statistical aspects of ionization without extensive computations, it can provide a first approximation to some of the gross features of behavior.

A collection of interstellar O trajectories originating at 50 AU on a single plane (of a cylindrically symmetric system, with flow axis along the abscissa), obtained with a standard

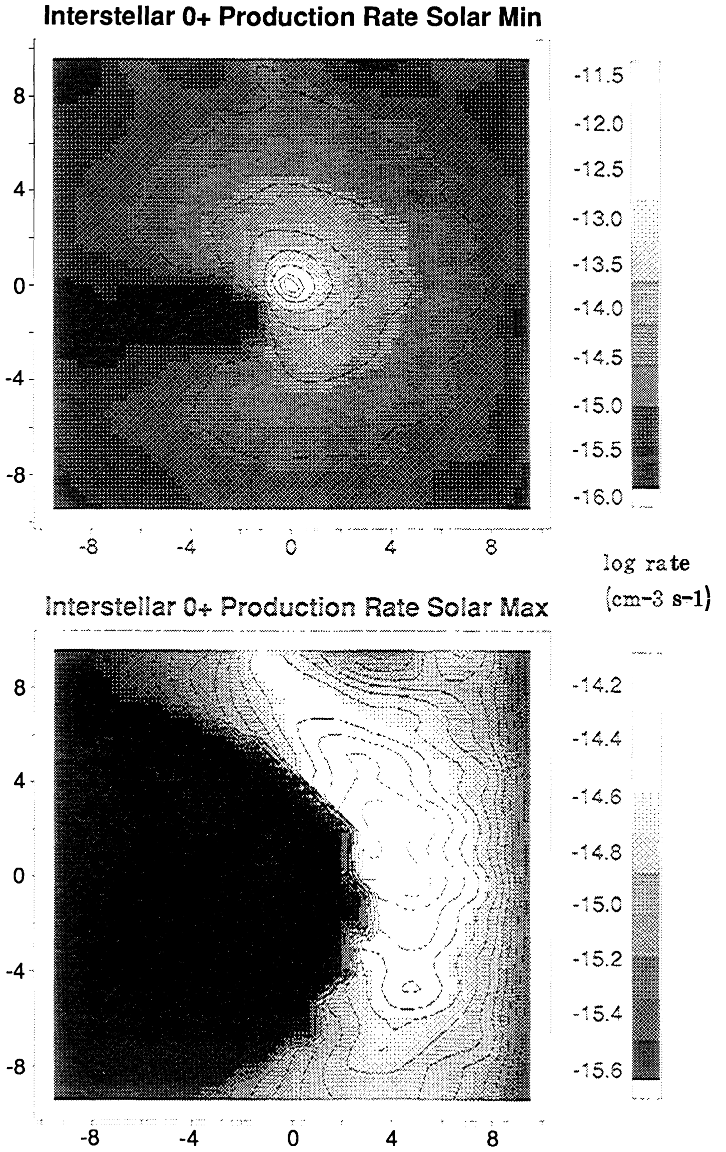

Figure 6. Contours of production rate of O^+ from the interstellar gas in the heliosphere based on the density contours in Figure 2.

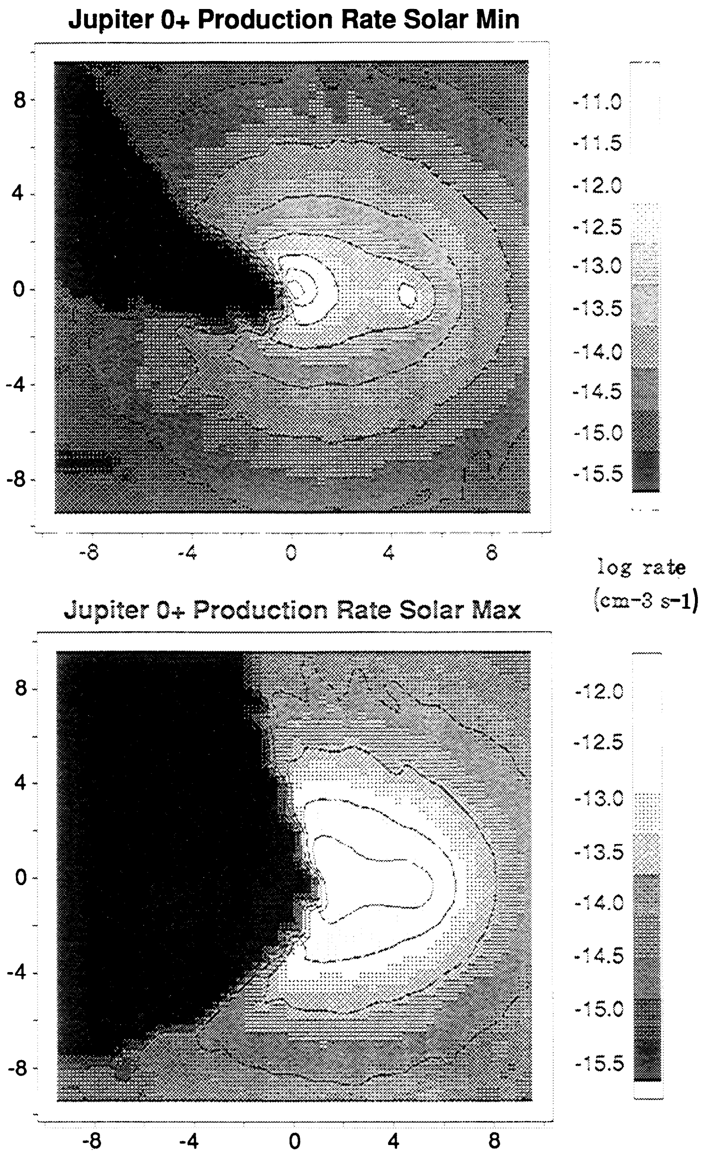

Figure 7. Same as Figure 6 but for O^+ from the Jovian oxygen in Figure 4.

numerical equation of motion solver for the gravitational effects, is shown in Figure 1. These were computed assuming a 20 km s^{-1} interstellar gas velocity relative to the Sun, and neglecting the approximately few kilometers per second thermal velocities expected for interstellar O [e.g., *Fahr,* 1990]. While current estimates of the heliopause distance are now greater than 100 AU [e.g., *Gurnett et al.*, 1993], it is here presumed that after the exclusion of ionized O (a ~30% reduction) and the filtering of neutral O (up to 90% reduction) at the heliopause mentioned earlier, neutral oxygen propagates practically unaffected until it reaches the outer solar system. This assumption is borne out by the calculations. The cumulative "probability" of ionization (as given by the integration over time of the inverse of the spatially dependent ionization rate) is tracked for each trajectory, which is terminated when the integrated probability for any of the three ionization processes is equal to one. Thus the trajectories indicate the ionization mean free paths. The two parts of Figure 1 take into account the expected solar cycle variation of about a factor of 4 in the photoionization rate but assume no solar cycle changes or nonuniformities in the solar wind parameters, which produce a smaller effect. The solar wind was assumed to flow radially at 400 km s^{-1} and to have a density of 10 cm^{-3} at 1 AU. While this value for the density is somewhat higher than average (by ~30%-50%), it allows for the existence of localized high densities near the ecliptic plane caused by stream interfaces and is not an unusual value [e.g., *Petrinec and Russell,* 1993]. The assumed electron temperature follows the approximate formulas suggested by *Axford* [1972], and the cross sections for electron impact ionization are as given by *Cravens et al.* [1987]. The photoionization

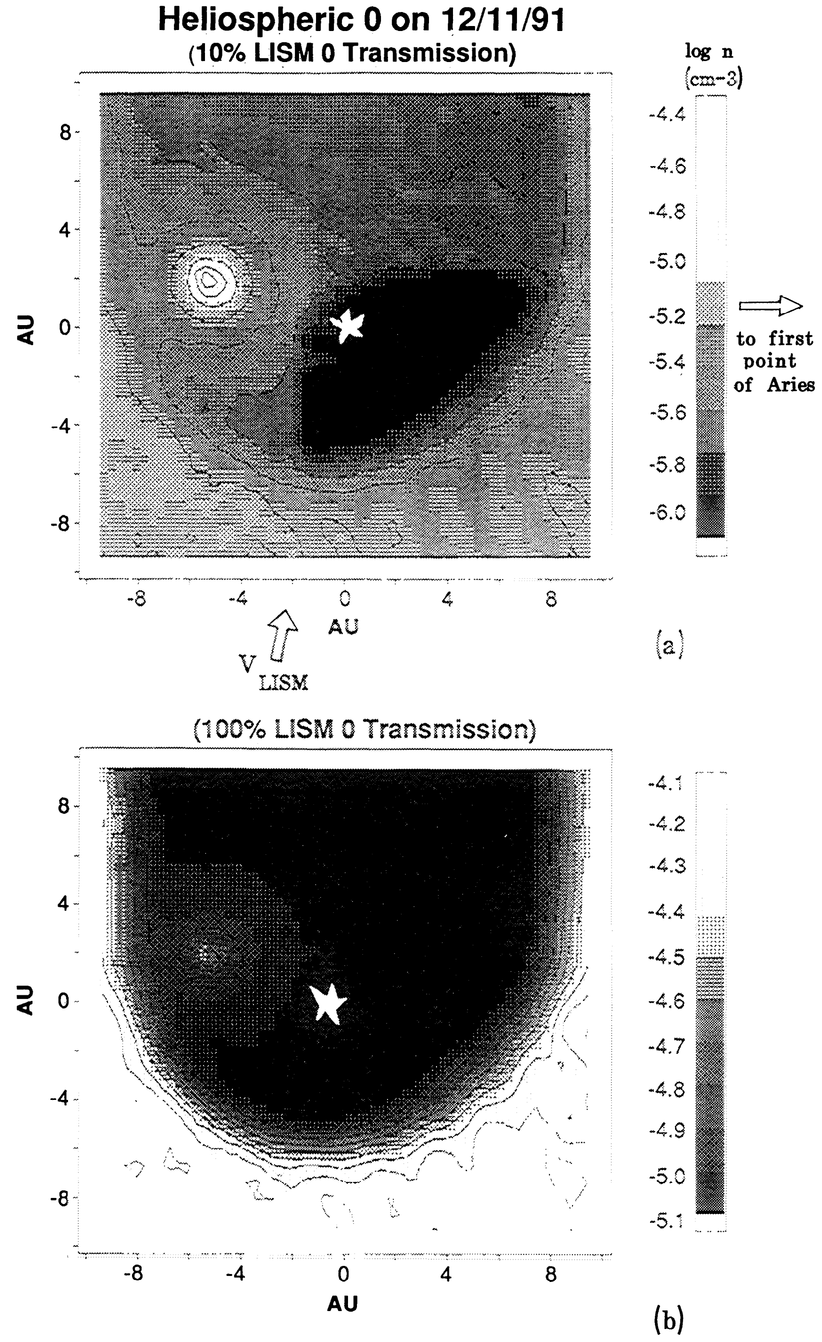

Figure 8. Neutral O density models for the heliosphere on December 11, 1991, when a Ulysses experiment to search for low charge state ions was conducted by *Geiss et al.* [1992]. Ulysses was located roughly between the Sun (designated by a white star) and Jupiter at 1.3-1.4 AU at the time. (a) 10% LISM O transmission assumed; (b) 100% LISM O transmission assumed.

rate used for solar minimum is $2.5\times10^{-7}/R^2$ (AU) s^{-1}, while charge exchange with the solar wind protons is treated with a fixed cross section of 8×10^{-16} cm^2. These trajectories are translated to inner heliosphere densities in Figure 2 by contouring the trajectory point densities obtained using a fixed time step and weighing them according to the source strength. Here and elsewhere in this paper, an LISM oxygen transmissivity of 10% is assumed in order to emphasize the possible contributions of the planetary source. The shape of the created "void" downstream of the sun in the neutral O is determined primarily by the photoionization process together with the assumed 20 km s^{-1} speed of the

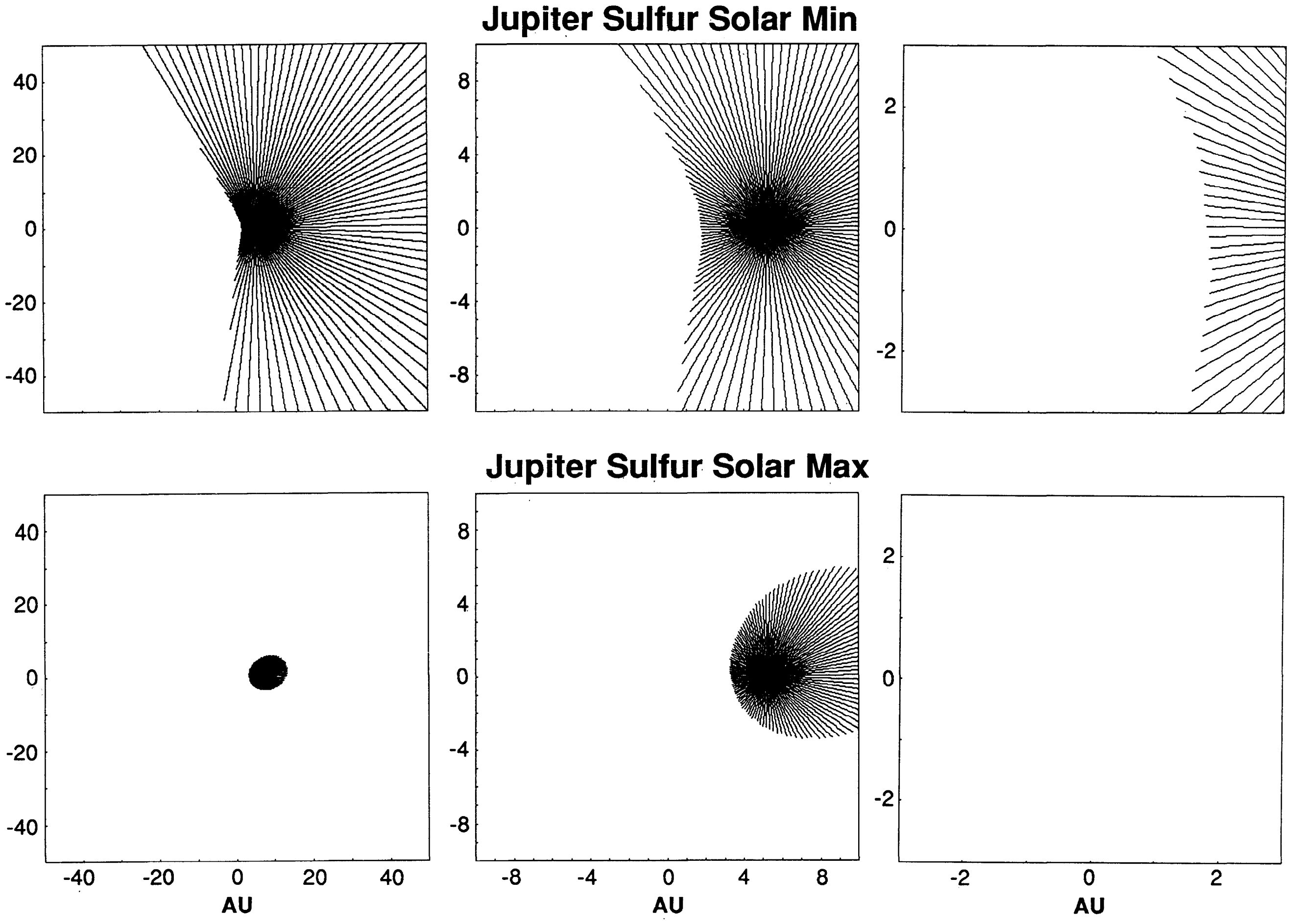

Figure A1. Same as Figure 3 but for Jovian sulfur.

neutral O. In nature, its sharp edge will be softened by the thermal motions of the gas as well as by the stochastic aspects of the ionization processes [see *Rucinski et al.*, 1993].

Figure 3 shows similar trajectories of O atoms from the most important planetary source, the Jovian source, which is here located at +5.2 AU on the abscissa. The Jovian O atoms radiate into the ecliptic plane from the equatorial inner magnetosphere at 75 km s^{-1} velocities, with a small correction to account for the orbital motion of Jupiter. (Here we ignore the ~13 km s^{-1} thermal velocity mentioned by *Cheng* [1986].) As for the interstellar O in Figure 1, a gap in the heliospheric population occurs where ionization ends the neutrals' trajectories. In this case, however, the shape and location of the gap differs because of the speed and directions of the Jovian neutrals. A further complication is introduced by the orbital motion of Jupiter, which carries the planet around an appreciable portion of its circumsolar path during the time of the plotted trajectories. The effect, shown in Figure 4, is that the gap in Jovian interplanetary O densities caused by ionization becomes spiral-shaped as the heliospheric azimuth of the downstream direction with respect to Jupiter changes with time. In a sense, ionization leaves its imprint on each "front" of neutral particles that has left Jupiter as it passes the Sun.

Oxygen Ion Sources

While highly ionized oxygen ions are expected to exist in the heliosphere as part of the solar wind [e.g., *Bame*, 1972], here we will be concerned only with potential sources of low charge state ions. As noted earlier, these are of special interest because of their possible interpretation as ionized gas of interstellar origin and because pickup ions are thought to be the source of the ACR.

It was mentioned above that although some fraction (~30-50% according to *Fahr* [1991] and *Rucinski* [1992]) of the interstellar medium oxygen is probably ionized, this intrinsic interstellar oxygen ion population is deflected around the heliosphere with the interstellar plasma. The interstellar oxygen hence only contributes interplanetary ions through ionization of the penetrating neutral component. In the present test particle picture, O^+ ions are produced where the O atom trajectories stop. To a first approximation, the heliospheric O^+ source created by the interstellar gas is then

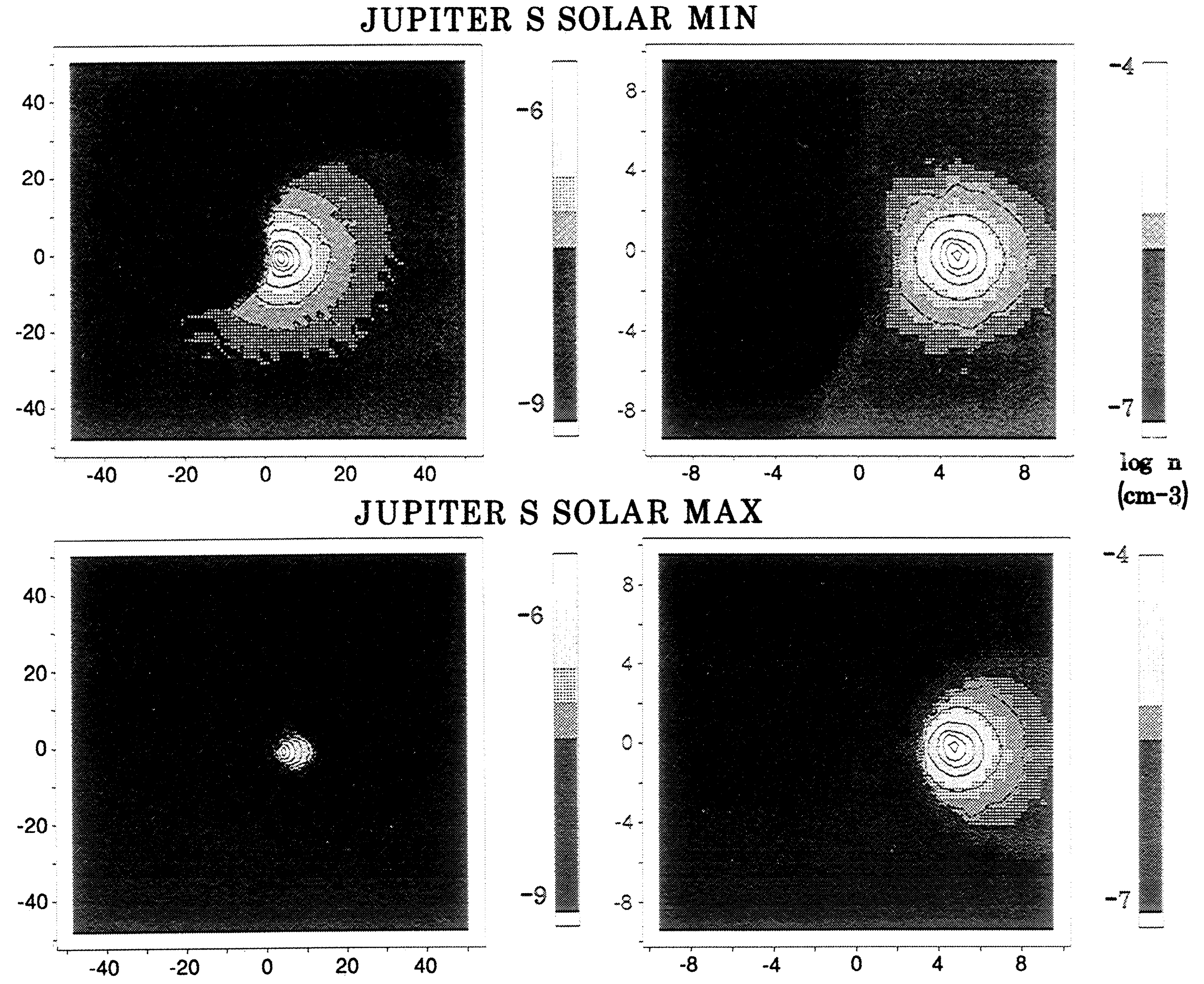

Figure A2. Same as Figure 4 but for Jovian sulfur.

inferred to be in the (three dimensional) shape of the boundaries of the voids in Figure 2. The O^+ ions born from this source are picked up by the solar wind and eventually move radially outward as illustrated by the equatorial projections of the O^+ trajectories in Figure 5. These trajectories were calculated using a (unidirectional) Parker spiral heliospheric magnetic field model, with an assumed 400 km s^{-1} solar wind velocity. The same numerical equation of motion solver as was used for the O trajectories, with the force now given by the solar gravitational force plus the Lorentz force, $F = Ze(E+v\times B)$ with E the convection electric field $E=-V_{sw}\times B$, was used, although less computationally intensive drift approximations to the ion motion could alternatively have been applied. (Ze is the ion charge ($= e$, the absolute value of the electron charge here), v is the ion velocity, V_{sw} the solar wind velocity, and B the interplanetary magnetic field.) The pickup ion trajectories are generally insensitive to the polarity of the magnetic field, except that in the immediate vicinity of a heliospheric current sheet one would expect to find the polarity effects predicted for the higher-energy cosmic rays [e.g., *Jokipii*, 1986a].

It is clear from Figure 1 that not all of the interstellar neutral O source contributes to the O^+ ion population in the heliosphere. During solar minimum only about 10% of the neutral O trajectories entering inside of 50 AU do not pass through to the other side. During solar maximum this number increases to ~30%. Thus the interstellar oxygen ion source in the heliosphere is estimated to be weaker than the interstellar neutral source by approximately these amounts. In this test particle model the O^+ pickup ion source is located only at the surface containing the starting points (asterisks) in Figure 5. A better picture of the interstellar O^+ ion production rate in the heliosphere can be obtained by multiplying the neutral densities in Figure 2 with the position-dependent ionization frequencies. Figure 6 shows the resulting ion production rate contours. The total number of ions produced per second by this source in a

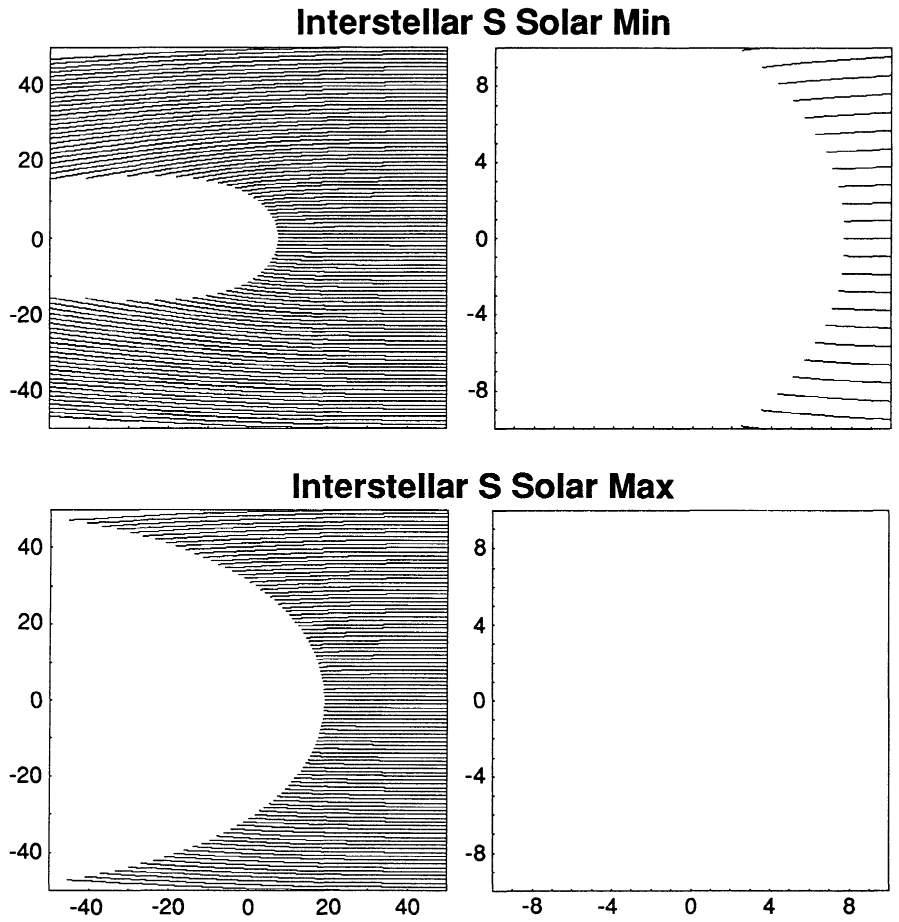

Figure A3. Same as Figure 1 but for interstellar sulfur. The dark right-hand edge shading is an artifact of the contouring procedure used.

50×50×50 AU^3 volume (assuming this distribution is independent of heliolatitude) is ~10^{29} - 10^{30} s^{-1}. According to Figure 1, the closest approach of typical interstellar O atoms to the sun (along the flow streamline through the Sun) occurs at ~5.0 AU at solar maximum and at ~1.7 AU at solar minimum. Thus this model suggests that the contribution of interstellar O to the O^+ ions in the heliosphere is at its minimum inside of the orbit of Jupiter at solar maximum or inside of the orbit of Mars at solar minimum. Moreover, both the ion trajectories (Figure 5) and the ion production rate contours (Figure 6) indicate that there should be a characteristic gap in the pickup ion population of interstellar origin at azimuthal positions in the heliosphere opposite the direction of the incoming gas flow. Since the LISM flow direction is presumed constantly directed toward ~75° heliocentric longitude [*Holzer*, 1989], this gap should always occur at about that position. The upwind-downwind asymmetries in the interstellar pickup ion source were recently modeled in three dimensions by *Rucinski et al.* [1993]. Their conclusions regarding the general nature of the asymmetries appear similar to those reached here, although detailed comparisons of the predicted O^+ fluxes have not yet been carried out.

Other oxygen ions are created in the heliosphere in the same way from the planetary neutral populations described above. However, the different spatial distributions and velocities of the planetary neutrals results in different O^+ source locations. As before, the boundaries of the voids in the neutral distributions (Figure 4) provide the source of O^+ pickup ions in the test particle model. The ends of the Jovian neutral trajectories (Figure 3) and hence ion trajectory origins lie closer to the sun than their interstellar counterparts because the Jovian neutrals approach the Sun at ~75 km s^{-1} while the interstellar neutrals move at only 20 km s^{-1}. Trajectories of picked up O^+ ions starting at these points are also shown in Figure 5. The heliocentric longitude of the gap in the Jovian pickup ion population will move with respect to the LISM O^+ gap as the Jovian year progresses.

The Jovian pickup ion source strength can be estimated by noting that ~10-50% of the Jovian neutral trajectories stop in the heliosphere depending on the solar cycle phase. This

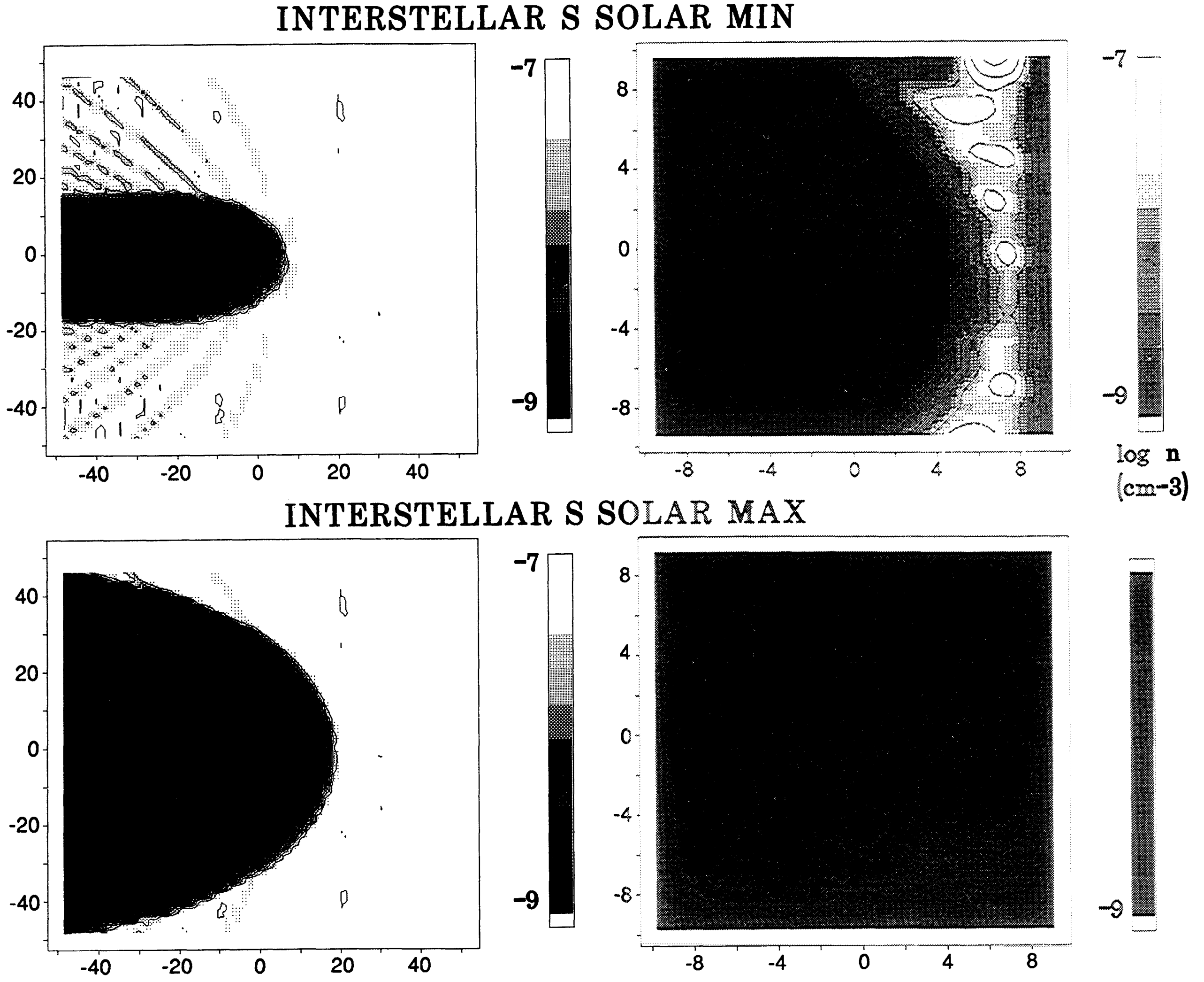

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Figure A4. Same as Figure 2 but for interstellar sulfur.

implies ~1-3×10^{28} O$^+$ s^{-1} are created. However, again the test particle model is deficient in its neglect of the ionization that occurs elsewhere in the Jovian O nebula. Jovian O$^+$ production rates in the heliosphere obtained by multiplying the neutral densities in Figure 4 by the local ionization frequencies are shown in Figure 7. The implied integrated source rates for the heliosphere are consistent with values between the above estimates and the full neutral O production rate of ~1-5×10^{28} s^{-1}. These rates of injection can be compared with the rates from the other planetary sources of O$^+$.

Polar winds at the magnetized planets and ions from the ionization of the trapped atomic oxygen exospheres of Venus and Mars are known direct producers of escaping O$^+$. Ionization of the Venus and Mars oxygen exospheres can supply O$^+$ at an upper limit of ~10^{24} s^{-1} to ~10^{25} s^{-1} according to calculations by *Zhang et al.* [1993]. For Earth, the polar wind O$^+$ source is estimated at ~10^{25} s^{-1} [*Waite et al.*, 1985]. The O$^+$ polar wind source strength at Jupiter is undetermined, but it should be a small fraction of the ~ 10^{28} s^{-1} rate estimated for hydrogen by *Nagy et al.* [1986]. The strengths of the polar wind sources from the remaining giant planets are unknown. In any case, since the origins of polar wind ion trajectories are located at the planets, only the O$^+$ population in the outer solar system would be affected. The "leakage" of magnetospheric ions through planetary magnetopauses [e.g., *Sibeck et al.*, 1988] is probably a relatively minor additional contributor. Thus Jupiter appears to be the major noninterstellar source of picked up O$^+$ in the inner solar system in the absence of a substantial cometary source. It is also the most widespread because of the neutral O trajectories and velocities. According to Figure 5, this source is characterized by an azimuthal gap of varying width that occurs roughly at the position in the heliosphere opposite Jupiter's location. Since the Jovian neutral wind is concentrated near the equatorial plane of Jupiter, this source

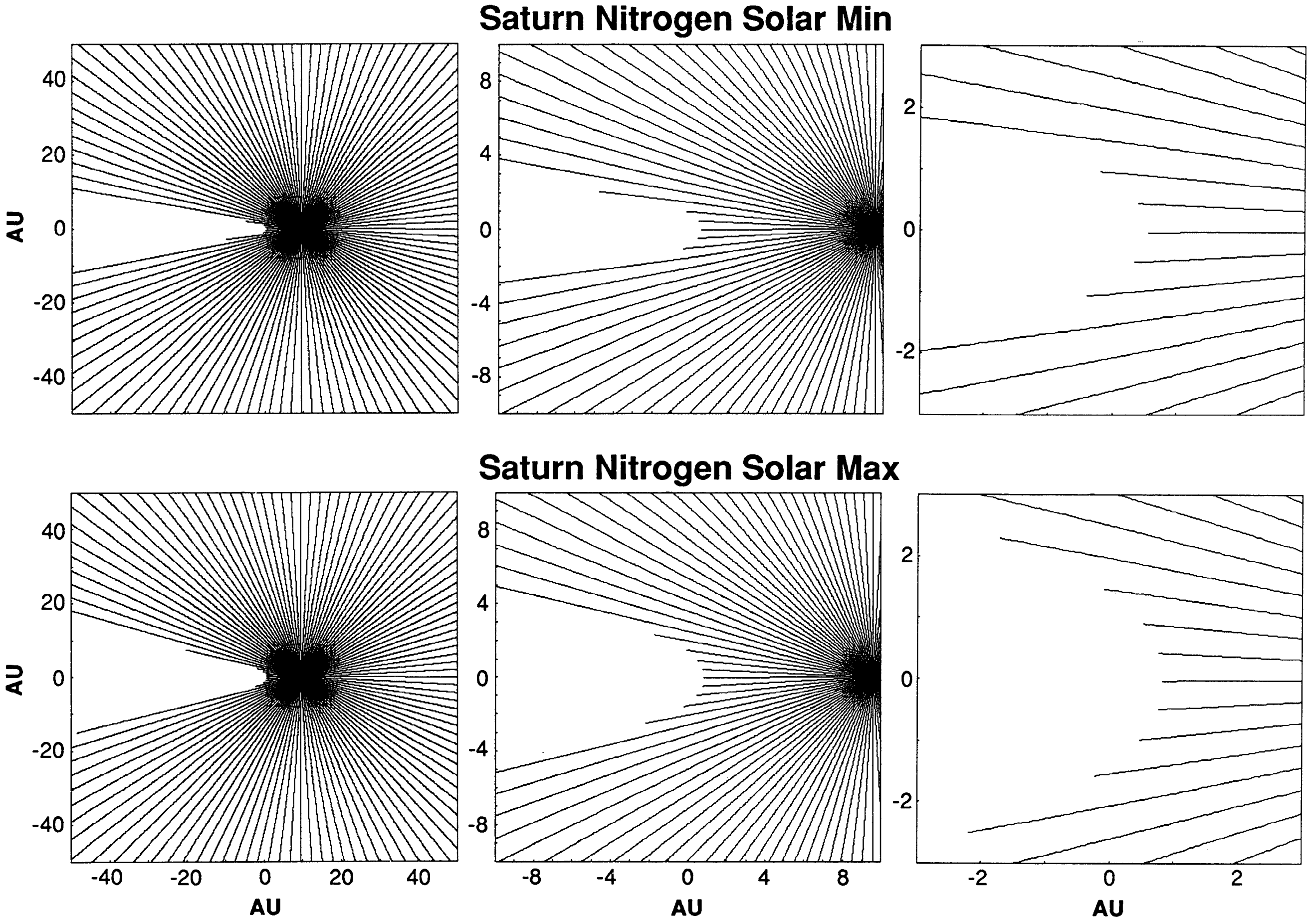

Figure A5. Same as Figure 3 but for Kronian nitrogen.

is expected to be unimportant at high heliospheric latitudes. While the O source thermal velocities will smear this picture somewhat, these basic features are not expected to be destroyed. An interesting additional characteristic of the Jovian source is that the near coincidence of the ~11 (Earth) year solar cycle and the ~12 year length of the Jovian orbital period implies that the Jovian source at any heliospheric locale is modulated at about the same period by both Jupiter's motion and solar activity. Hence separation of these two effects requires careful consideration.

A key point made by this analysis and the analysis of the interstellar O^+ source is that the primary Jovian O^+ flux should not simply increase as Jupiter is approached nor should the interstellar O^+ flux increase as the heliospheric boundary is neared. Because both sources depend on ionization near the Sun, the pickup ions originate primarily from a wide range of heliocentric longitudes at locations in the inner heliosphere (see Figures 6 and 7) that are well removed from their neutral source regions (although the Jovian source has a secondary maximum near Jupiter). This is in contrast to the previously described polar wind and exospheric O^+ sources that are located at the planets' positions. The latter "point" sources produce relatively narrow streams of outward moving ions confined to the planetary wakes [e.g., *Russell and Neugebauer*, 1981].

The pickup O^+ ions from the interstellar and Jovian sources should have characteristic distribution functions. In the absence of the isotropizing effects of scattering (such as occurs in the inner parts of cometary atmospheres, or near the boundary of the heliosphere where the pickup ion density is a substantial fraction of the total) their pitch angles will reflect the heliocentric distance of their pickup as well as the history of the forces they experience while moving through the heliospheric field structures. Similarly, in the absence of local acceleration in structures such as interplanetary shocks, their energy spectra should reflect their initial velocities, the strength of the convection electric field as experienced from the point of their first acceleration, and any "adiabatic deceleration" [e.g., *Jokipii*, 1986a] that occurs later in the expanding interplanetary medium. Analyses of the pickup ion distribution functions from the different sources is beyond the scope of this discussion but can be addressed using a similar model as a starting point (also see *Rucinski et al.* [1993]).

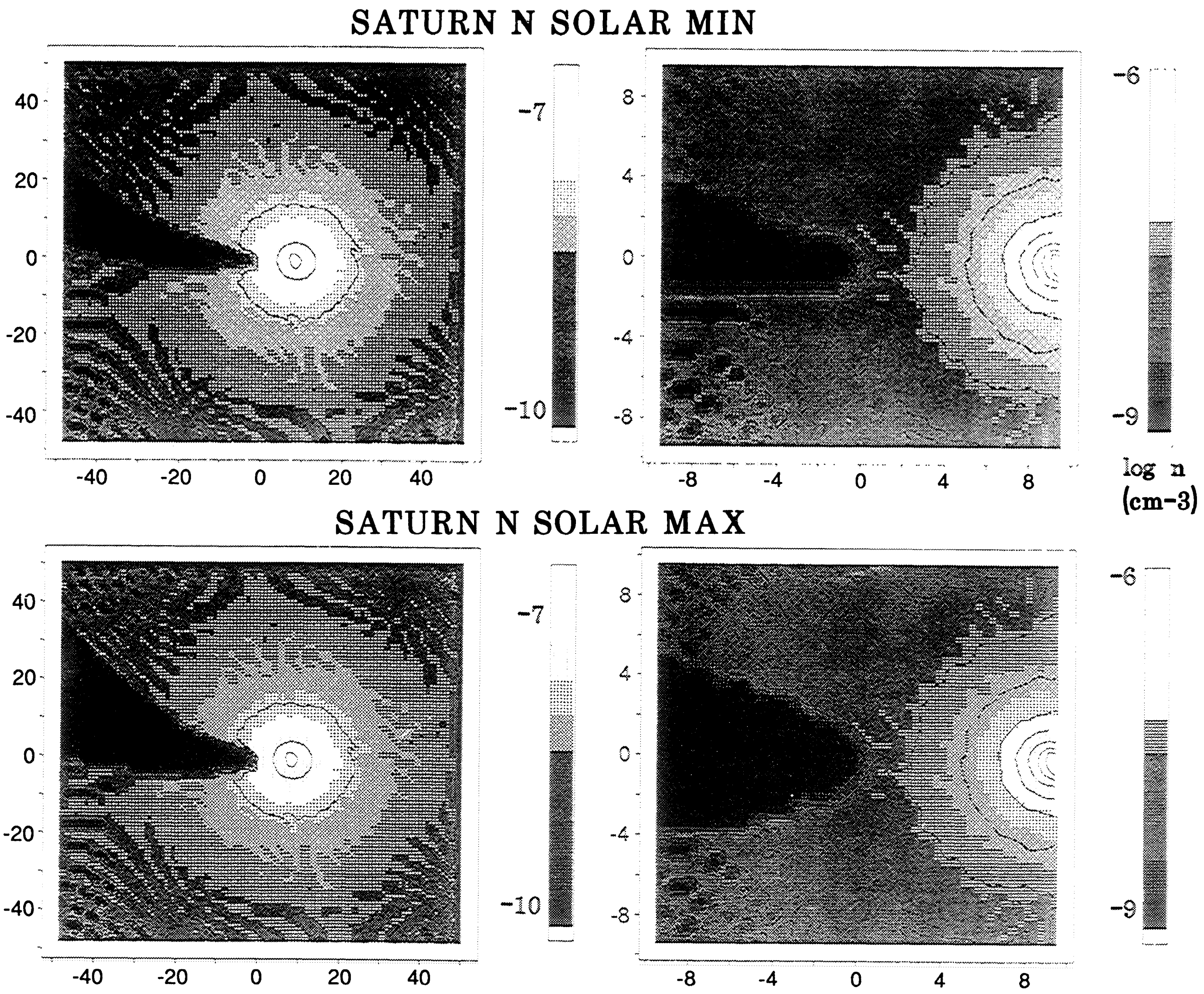

Figure A6. Same as Figure 4 but for Kronian nitrogen.

Comparison of Sources

An idea of the oxygen distribution in the heliosphere at a particular time can be obtained by calculating model densities as described above for the known steady planetary sources at Mars, Venus, Jupiter, and Saturn and adding them to the interstellar source. As an example, we consider the date December 11, 1991, when solar activity, and thus the EUV flux, was ~ 20% below maximum level. On this date the Ulysses spacecraft SWICS experiment searched for O^+ at ~1.3-1.4 AU on its way to Jupiter [*Geiss et al.,* 1992]. Figure 8 shows "portraits" of the equatorial inner heliosphere in neutral oxygen at this time, assuming either 10% or 100% LISM O transmission. Here the interstellar source is shown flowing toward the direction ~75° from the first point of Aries (to the right in these plots). The contributions of the Saturn, Mars, and Venus sources to Figure 8 are imperceptible. Jupiter (at left center) appears to dominate the neutral oxygen population in the inner heliosphere where the SWICS observations were made; however, the "edge" of the interstellar population is sharp because of the nature of the present model. The degree to which this edge is smeared by thermal velocity or the probablistic effects and irregularities associated with the ionization processes is clearly a factor in the detection of the planetary source, especially in the case of 100% LISM O transmission. Nevertheless, the pickup O^+ from the Jovian source should have been present at Ulysses at this location with a flux of ~10 cm^{-2} s^{-1}. If the picked up O^+ velocities ranged between zero and 2 V_{sw} sin α, where α is the local garden hose angle at the site of pickup and V_{sw} averaged near 380 km/s, these ions should have been detectable at energies at and below ~50 keV. Given that the SWICS acceptance angle covers the range within 60° of the Earth-spacecraft line, the instrument aperture should have intercepted some of these Jovian ions. Measurement of the interstellar component, with a flux at least ~10x greater, appears most favorable at heliocentric distances beyond ~5 AU where the bulk of the interstellar O^+ are produced at Jupiter's heliolongitude at this time.

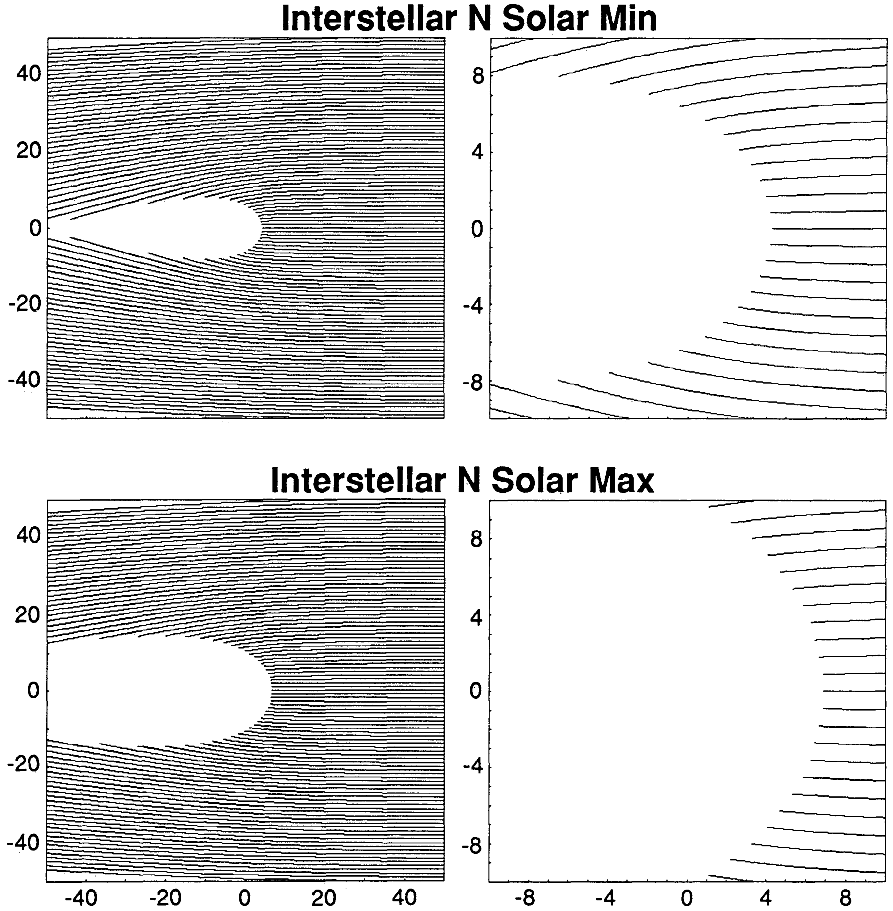

Figure A7. Same as Figure 1 but for interstellar nitrogen.

The latest Ulysses results reported by *Geiss et al.* [1994] show a substantial radial gradient between 1 and 5 AU over the period December 1991 through mid-1992, but the contribution of the planetary flux to that gradient is considered insignificant by the authors. Decreasing solar activity in 1992 would indeed move the "edge" of the LISM source into the orbit of Jupiter. The LISM O transmissivity at the heliopause then determines how much the Jovian O^+ contributed to the measured flux. Geiss et al.'s conclusion suggests that the LISM O transmission is high but that conclusion does not rule out the possibility of Jovian O^+ detection under other circumstances. For example, the WIND spacecraft may detect the Jovian component as it monitors the solar wind at 1 AU.

Conclusion

Analysis of the primary internal and external sources of oxygen in the heliosphere suggests that the origin of the neutral O at a given location will depend on heliocentric distance, heliolongitude, heliolatitude, the relative positions of the planets, and the phase of the solar cycle. In particular, the Jovian neutral wind must contribute at some level, but its importance depends on the level of transmission of LISM O at the heliopause. The interior boundaries of the neutral distribution from each source, as determined by the effective ionization processes and rates, describe the major source regions for O^+ pickup ions in the heliosphere. Interpretations of low charge state ion observations thus require consideration of the heliospheric and planetary configuration, together with the solar ionizing flux, at the time the data are obtained. The possibility of detection of the extended planetary "disks" is also of interest from a planetary science perspective. While the emphasis here has been on the escape to interplanetary space of planetary particles, it is worth noting that planets will also capture or "accrete" both interstellar neutrals and neutrals from other planets by charge exchange in their plasmaspheres or ionospheres.

Considering that the internal sources of O are certainly responsible for implanting low charge state, low-energy pickup ions in the solar wind, one can ask whether they might also make a significant contribution to the anomalous cosmic rays in the heliosphere. In principle any picked up O^+ ion, regardless of its origin, can be the seed particle that is accelerated by statistical [e.g., *Klecker*, 1977] or termination shock [*Jokipii*, 1986b] processes. The answer should depend on the relative source strengths estimated

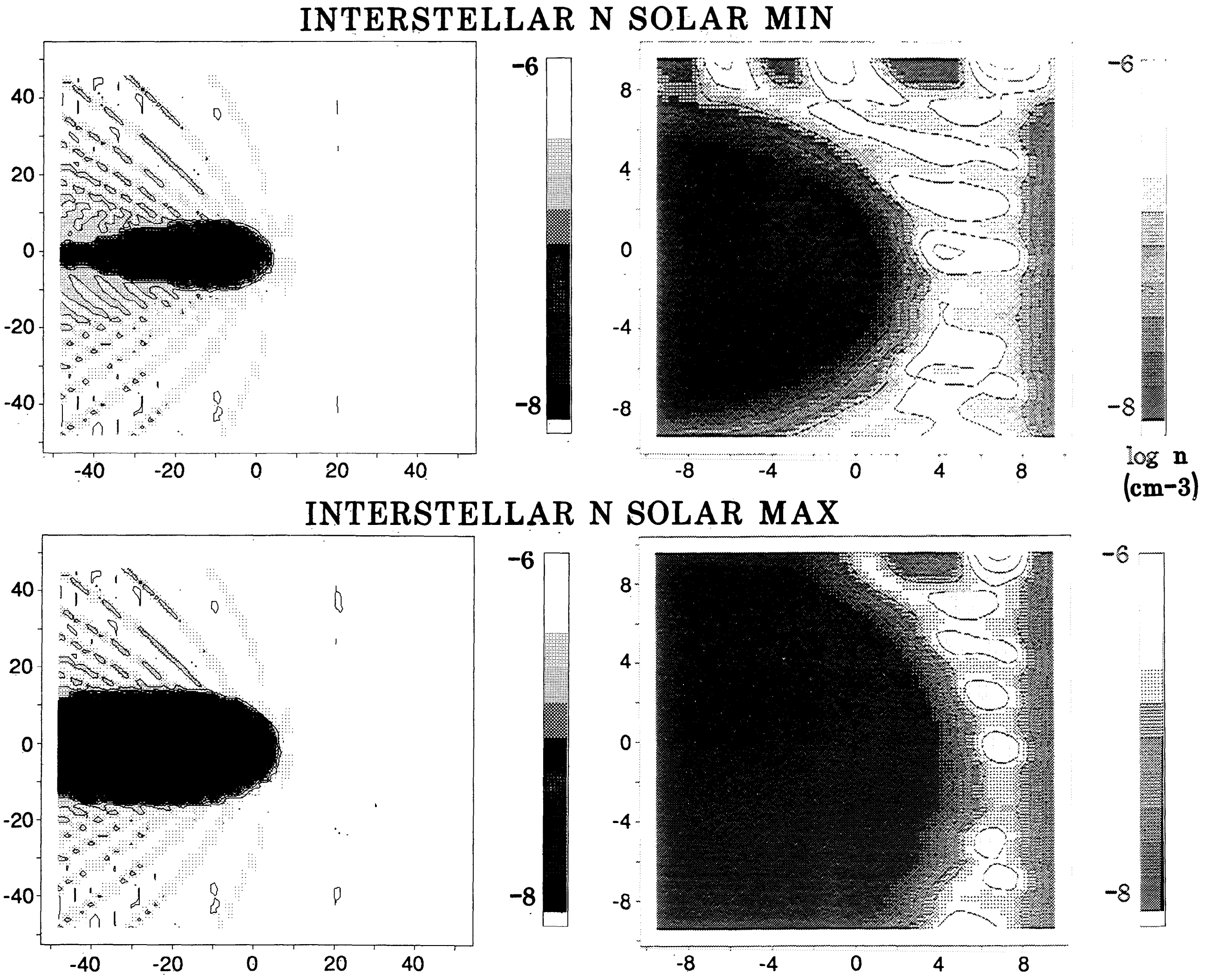

Figure A8. Same as Figure 2 but for interstellar nitrogen.

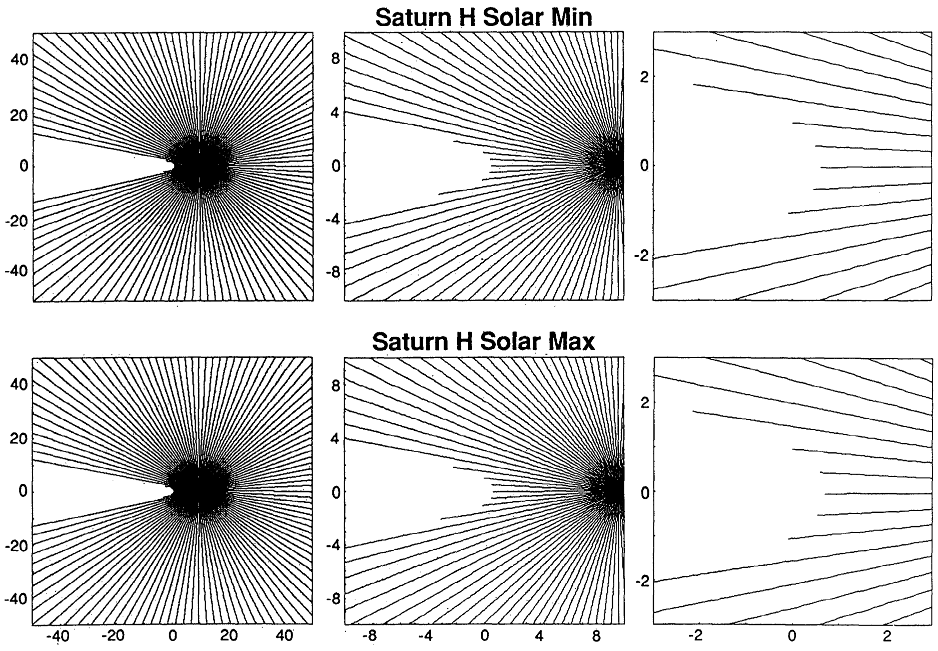

Figure A9. Same as Figure 3 but for Kronian hydrogen.

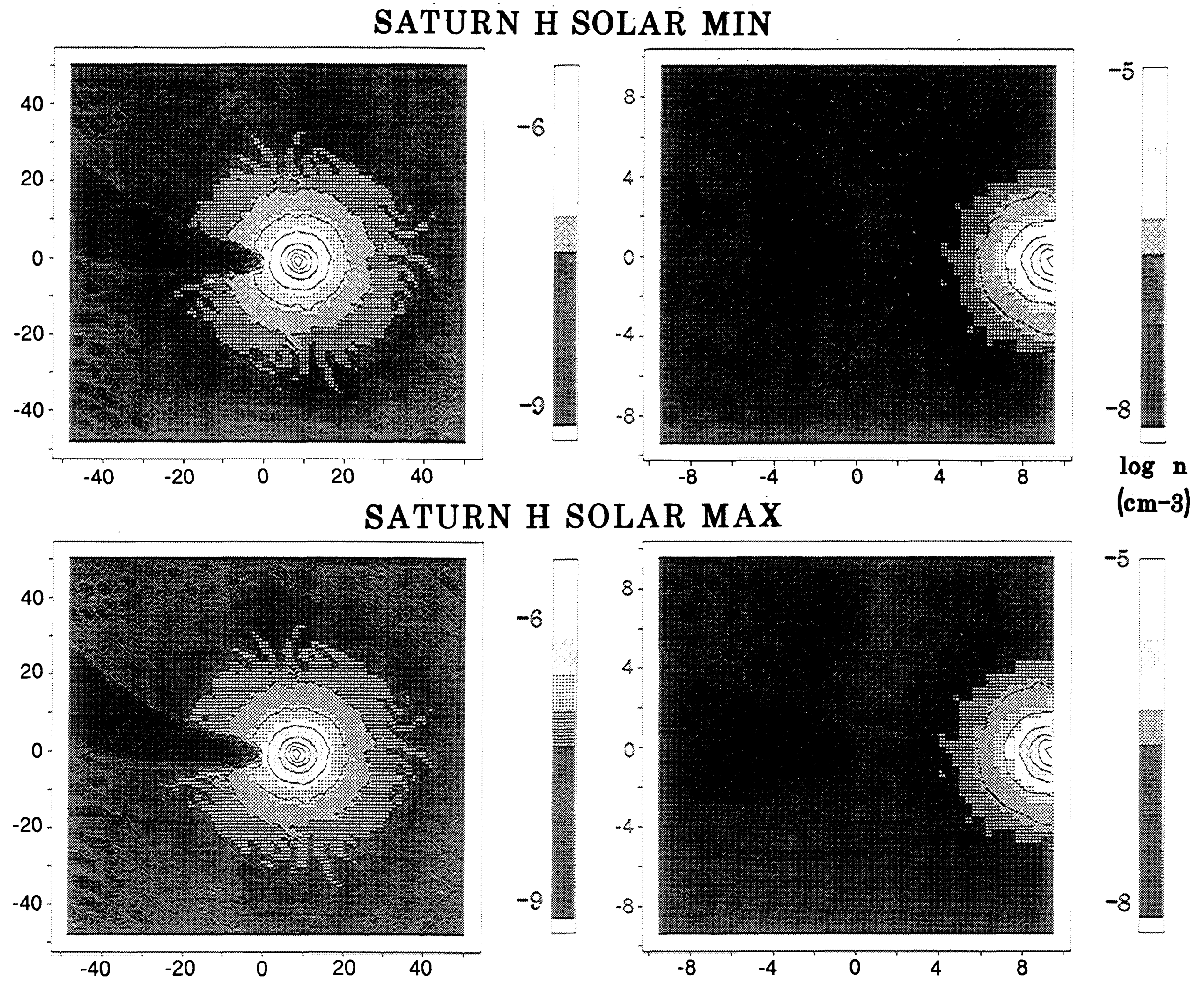

Figure A10. Same as Figure 4 but for Kronian hydrogen.

earlier. According to those estimates of ion production rates, the largest planetary source at Jupiter can supply up to $\sim 10^{28}$ O^+ s^{-1} at solar maximum compared to $\geq 10^{30}$ O^+ s^{-1} from the interstellar source. Thus the interstellar source, to the extent that its density and transmitted fraction are correctly guessed, is the strongest potential source of picked up O^+ in the heliosphere as a whole. On the other hand, signatures in the anomalous component such as an inferred persistent low heliolatitude source region, regardless of the solar dipole polarity, or any suggestion in observations that the picked up O^+ source for the ACR occupies only half the heliosphere during solar maximum (e.g., an approximately annual cycle in the ACR flux measured at Earth that is coupled to Jupiter's orbital phase instead of the LISM flow direction) could signal a Jovian source contribution. Such signatures have not been reported, although some analyses of temporal variations have been carried out with data from the Voyager 1-2 and Pioneer 10 spacecraft rather than with near-Earth monitors (but see *Mewaldt et al.* [1993]). In any case a contribution from internal sources of O is expected in the low-energy population of O^+ pickup ions in the inner heliosphere. Future analyses of spacecraft observations will ultimately reveal the importance of this source.

Appendix: Other Constituents

In a sense the planetary oxygen described above forms part of an "atmosphere" of the solar system. If this atmosphere is considered to include all planetary (neutral) exosphere populations that reach distances from their source(s) significant on the scale of the heliosphere, then there are several other constituents that merit mention. In addition to oxygen, the Io torus at Jupiter provides a comparable source ($\sim 10^{28}$ atoms s^{-1}) of interplanetary neutral sulfur (the torus sodium observed from the ground by *Mendillo et al.* [1990] is relatively confined to the space around the planet and so will not be included here). This atomic sulfur, like the oxygen, originates from charge exchange of corotating torus ions and so effectively radiates from near the planetary equator at ~ 75 km s^{-1} velocities.

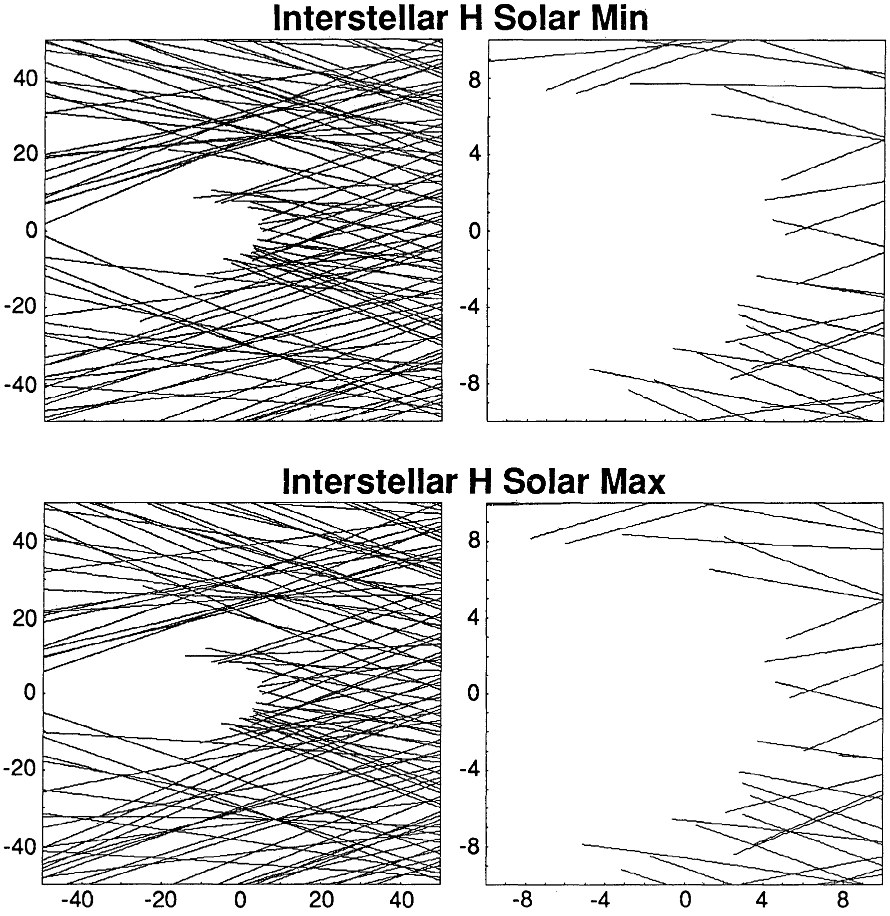

Figure A11. Same as Figure 1 but for interstellar hydrogen with a random "thermal" velocity component of 7.5 km s^{-1}.

Its trajectories and the resulting density distribution in the equatorial plane for solar maximum and solar minimum conditions are shown in Figures A1 and A2 in the same formats as in Figures 3 and 4 above. The photoionization and charge exchange rates used were those given by *Barbosa and Eviatar* [1986] with a factor of 4 reduction in photoionization rate assumed for solar minimum. According to cosmic abundance tables (e.g., as presented in *Bame* [1972, Table 3]) the interstellar sulfur density is less than that of oxygen by a factor of ~0.03. More important from the present viewpoint, the photoionization rate of sulfur is ~5× higher than that of oxygen. The result as illustrated by Figures A3 and A4 is that a much bigger hole is carved out of the interstellar sulfur, with the implication that the planetary source dominates throughout a much larger portion of the solar system than does the oxygen (although the oxygen is more widespread as seen in Figures 3 and 4). Of course, this hole could be significantly reduced in size if the interstellar sulfur temperature, which was neglected here, is comparable to the flow speed.

As noted by *Barbosa and Eviatar* [1986], Saturn's Titan torus is also a source of corotation-derived neutral "winds". In this case the important constituents are considered to be atomic nitrogen and hydrogen which emanate from low Kronian latitudes at velocities near ~200 km s^{-1}. The higher speed is a consequence of the greater average corotation velocity at the location of the Titan torus. Estimates of the source strengths for this nitrogen and hydrogen are ~3×10^{25} s^{-1} and ~4×10^{26} s^{-1} respectively. Using the photoionization rates from *Barbosa and Eviatar*'s [1986] values, and the charge exchange cross sections from *Axford* [1972], the trajectories and density distributions in Figures A5, A6, A7 and A8 are obtained. (The hydrogen trajectories shown were modified for Lyman alpha radiation pressure forces according to the formulation given by *Axford* [1972] with μ=0.8 for solar minimum and μ=1.2 for solar maximum). The interstellar counterparts of these are shown in Figures A9, A10, A11 and A12. In this case a "temperature" was added to the hydrogen by presuming an added randomly directed velocity component of 7.5 km s^{-1} (corresponding to a temperature of ~7000 °K). The practically negligible effect of the solar cycle on the hydrogen distributions results from the dominance of charge exchange and the neglect of solar cycle changes in the solar

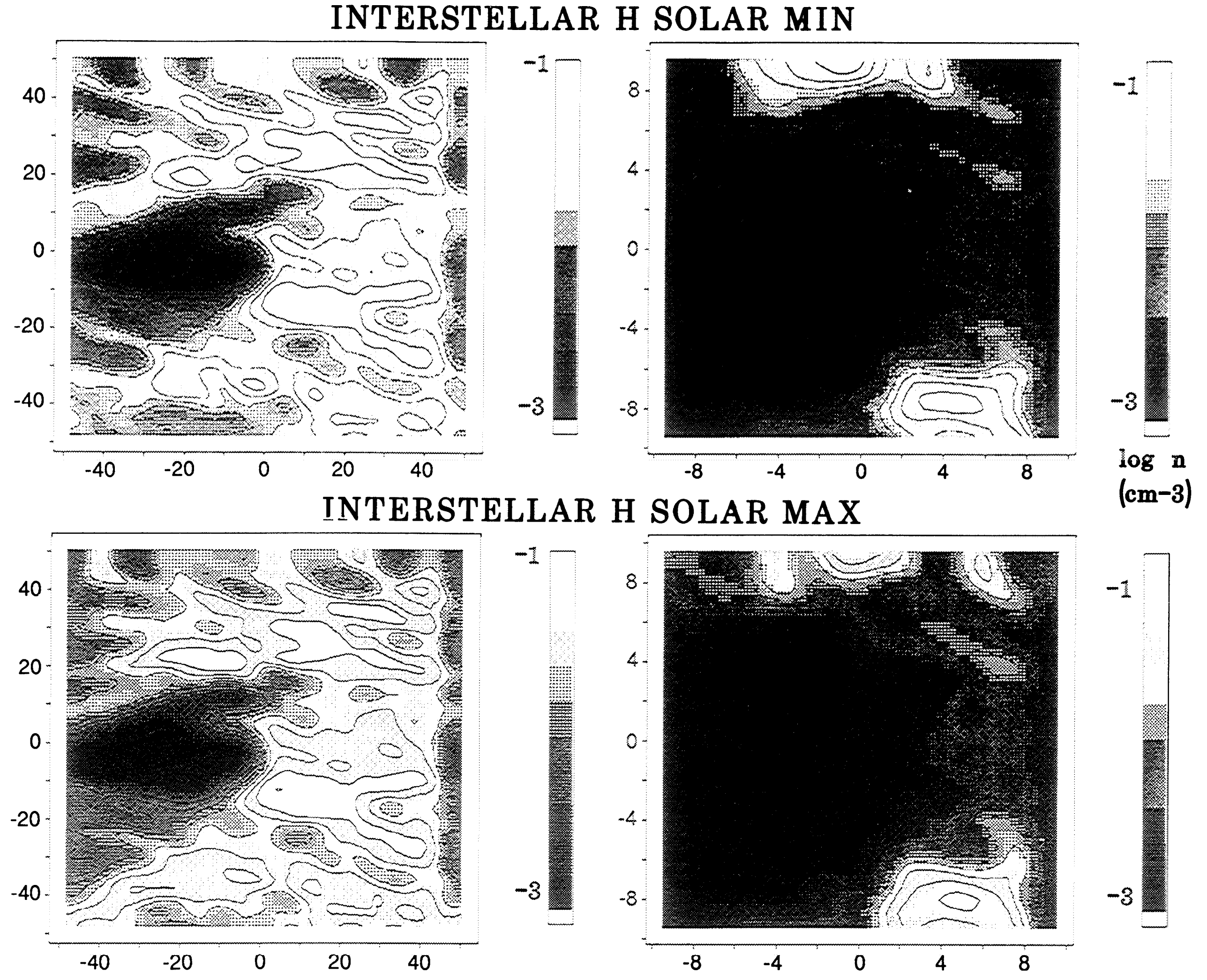

Figure A12. Same as Figure 2 but for the interstellar hydrogen in Figure A11.

wind in the present model. The nitrogen was assumed to have an interstellar abundance ~15% that of oxygen.

Together, the patterns of planetary neutral densities within the heliosphere presented in this paper reinforce the idea that local composition need not be cosmic. In addition to the fact that the solar radiation and solar wind have different filtering effects on the different inflowing interstellar constituents, planetary particles that have been "processed" in a variety of planetary source regions can affect what is measured.

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