Reports

Estimates of Mass and Angular Momentum in the Oort Cloud

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Estimates can be made of unseen mass (in the form of cometary nuclei) at the heliocentric distances between 3×10^3 and 2×10^4 astronomical units (AU) under the assumptions (i) that the Oort cloud is a rarefied halo surrounding the core (dense, inner cometary cloud) and (ii) that the mass and albedo of comet Halley is typical for comets both in the core and the Oort cloud populations. The mass appears to be approximately 0.03 solar masses, with angular momentum of the order of 10^{52} to 10^{53} g-cm²/s. This mass is of the order of the total mass of the planetary system before the loss of volatiles. This leads to an estimate of a mass $M_o \simeq 100\ M_\oplus$ (where $M_\oplus$ is the mass of Earth) concentrated in the Oort cloud ($r > 2 \times 10^4$ AU) with an angular momentum that may exceed the present angular momentum of the whole planetary system by one order of magnitude. The present angular momentum of the Oort cloud appears to be of the same order as the total angular momentum of the planetary system before the loss of volatiles.

BEFORE 1950 THE LARGE-SCALE structure of the solar system appeared to have been entirely established. In the center of the system there is the sun sharing 99.9% of the total mass and 2% of the angular momentum. Approximately 0.1% of the mass and 98% of the angular momentum are among the nine planets and their satellites. However, as was shown by Oort (*1*) in 1950, at the very remote periphery of the system there is one more component; a giant cloud of comets, which is known as the Oort cloud.

The aim of this report is to show that data on the number of comets in the Oort cloud, data from the Vega mission, and observational data for short and long period comets seem to indicate that the standard view on the large-scale structure of the solar system should be significantly changed. In particular, we argue that most of the angular momentum of the solar system must be not in the planets, but in the Oort cloud. The inner dense core of this cloud possibly contains a mass exceeding the total mass of all planets.

One of the most important results of the Vega mission was the determination of the mass of the nucleus of comet Halley. According to Sagdeev *et al.* (*2*), the mass derived from nongravitational acceleration of the nucleus is $M_H = 3 \times 10^{17}$ g (the minimum and maximum values may differ from the presented one by about a factor of 3) and the volume of the comet Halley nucleus, which has been derived from in situ measurements, is 585 ± 141 km³ (*3*). Assuming the density of this comet nucleus to be of the order of $\rho = 1$ g/cm², we find from this volume $M_H \simeq 6.3 \times 10^{17}$ g. The albedo value $A = 0.04^{+0.02}_{-0.01}$ (*4*) was another unexpected result, because it was substantially lower than the predicted value. At the same time the albedo of some short period (SP) comets (without coma) was measured by an infrared technique. These albedos were found to be as low as that of P/Halley [$A \simeq 0.02$ to 0.06; see the review by Spinrad (*5*)]. It is therefore reasonable to propose that such a value of albedo is typical for SP comets. Taking a value of albedo $A = 0.055$, Svoren (*6*) found the average radius of 14 SP comets, observed at large heliocentric distances (supposedly without coma) to be equal to $R_{SP} \simeq 4.4$ km. For $A = A_H = 0.04$, we find $R_{SP} \simeq 5.2$ km and $M_{SP} \simeq 2.9 \times 10^{17}$ g for a density equal to $\rho \simeq 0.5$ g/cm³. The effective radius of the sphere R_H with volume equal to the volume of the nucleus of P/Halley is equal to $R_H \simeq 5.3$ km. Thus, we propose that the mass and size of the nucleus of P/Halley are typical for SP comets, and are close to average values.

At the same time, "new" (observed) comets coming from the Oort cloud cannot have nuclei sizes and masses on the average smaller than R_{SP} and M_{SP}. That is,

$$\overline{R}_{SP} \lesssim \overline{R}_{new},\ \overline{M}_{SP} \lesssim \overline{M}_{new} \qquad (1)$$

if, of course, one did not suppose that "new" and SP comets have different origins. As was shown recently by Duncan *et al.* (*7*), SP comets, which are mostly in prograde, low-inclination orbits, could not arise from gravitational scattering of any spherical population of comets (such as the Oort cloud). They concluded that SP comets arise from cometary belt in the outer solar system. Such a cometary belt, perhaps, could be just the innermost extension of the inner Oort cloud (the core). The core is expected to be flattened, because the comets apparently are formed in a rotating protosolar disk. The cometary orbits in this case must be prograde. Both of the above facts are connected with a rarity of star passages through the core because of its small dimensions [$r < 2 \times 10^4$ AU (*8*)]; this results in a low efficiency of their thermalizing action. These rare stellar passages seem to cause only cometary showers (*8*). As a matter of fact, analysis of observations of nearly parabolic comets at remote helicentric distances (*6*) shows that the average value of the radius for such long period (LP) comets with the average albedo $A_{LP} = 0.65$ is $R_{LP} \simeq 5.8$ km. This is a result of selecting those 11 LP comets from 67 comets observed at great helicentric distances, r, whose brightness is governed by the law corresponding to the comets with bare nuclei. If the average value of albedo for such comets is less (that is, $A_{LP} < 0.65$), then the actual value of the R_{LP} would be even larger. Thus, the estimated size and mass of the nucleus of P/Halley give a lower limit for the size and mass of the nucleus of the "average new" comet, coming from the Oort cloud.

We shall assume throughout that the mass of a typical comet in the core and in the Oort cloud is of the order of $M \simeq M_H \simeq 3 \times 10^{17}$ g [see the paper by Marochnik *et al.* (*9*) for the more extended discussion of the value of the average cometary mass].

Estimates of the present number of comets in the Oort cloud give a value of the order of $N_o \simeq 2 \times 10^{12}$ (*10, 11*) and the thickness of the shell that contains them is of the order of $r = r_e - r_i$, where $r_i \simeq 2 \times 10^4$ AU is the internal and $r_e \simeq 5 \times 10^4$ AU is the external radius of the shell (*8, 10, 12*). Assuming the mass of a typical comet in the Oort cloud is $M \simeq M_H \simeq 3 \times 10^{17}$ g we find the total cloud mass is of the order of $M_o \simeq 100\ M_\oplus$ in contrast to, for example, Weissman's estimate (*13*) of $M_o \simeq 7$ to 8 $M_\oplus$ obtained before the comet missions. Thus, the first conclusion is that a very substantial mass $M_o \simeq 1/4\ M_p$ (where M_p is the total mass of the planets) is probably situated in the periphery of the solar system.

The hypothesis according to which comet nuclei are formed in the remote parts of the

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protosolar nebula either in situ (*14, 15*) or at distances of hundreds or thousands of astronomical units from the sun (*16, 17*) is the most preferable among the hypotheses on comet origin in view of cosmochemical data (see below). Moreover, the mass of the Oort cloud appears to be too large to explain its origin by ejection of the comet nuclei from the Uranus-Neptune zone by the planetary gravitational perturbations (see below).

In this case the angular momentum of that part of the protosolar disk, from which the comets of the Oort cloud were formed, should be conserved to within an order of magnitude owing to the isotropic (or quasi-isotropic) character of growth of the dispersion of the comet velocities in the Oort cloud as a result of randomly passing stars.

Let us estimate the angular momentum of the Oort cloud assuming that the cometary nuclei were formed in a periphery of the protosolar nebula and therefore the Oort cloud should conserve the main portion of its initial angular momentum.

The angular momentum of an "average" comet with the mass $M = M_{LP} = M_H$ in the solar gravitational field equals

$$j \equiv M_H r^2 \dot{\varphi} = M_H [G M_\odot a (1 - e^2)]^{1/2} \quad (2)$$

where e is the eccentricity, a is the semimajor axis of the orbit, $\dot{\varphi}$ is the angular rotation rate, and G is the gravitational constant.

The Oort cloud must be thermalized (*8, 29*) and should look like a spheroidal structure. The fraction of binaries (or comets) with thermalized orbits (that is, in statistic equilibrium) with the eccentricities between e and unity is just (*8, 21, 22*):

$$F_e = 1 - e^2 \quad (3)$$

so that between zero and e the fraction is $1 - F_e = e^2$. Thus in the interval $(e, e + de)$ there is a fraction of "thermalized comets" equal to $2ede$. Let the comet distribution in the Oort cloud over energy and eccentricities be $N(a, e)$ then in the intervals $(e, e + de)$ and $(a, a + da)$ there is

$$N dade = 2Cea^{-n} dade \quad (4)$$

where C is the normalization constant determined from the condition

$$N_o = 2C \int_0^1 ede \int_{a_{\min}^{(h)}}^{a_{\max}^{(h)}} a^{-n} da \quad (5)$$

where $a_{(\min)}^{(h)}$ and $a_{(\max)}^{(h)}$ are the minimum and maximum possible semimajor axes of comets in the Oort cloud. For example, $n = 2$ in the classical Oort model (*1*).

The total angular momentum of halo can be derived by multiplying Eq. 2 by Eq. 4 and integrating over all possible values of a and e (that is, $a_{\min}^{(h)} < a < a_{(\max)}^{(h)}$, $0 < e < 1$). As a result of integrating we find

$$J_o = \frac{2}{3} M_H N_o (G M_\odot a_{\min}^{(h)})^{1/2} \times \left(\frac{n-1}{n-3/2}\right)\left(\frac{1-\alpha^{-n+3/2}}{1-\alpha^{-n+1}}\right) \quad (6)$$

where $\alpha = a_{(\max)}^{(h)}/a_{(\min)}^{(h)}$.

Assuming $a_{(\min)}^{(h)} = r_i = 2 \times 10^4$ AU, $a_{\max}^{(h)} = r_e = 5 \times 10^4$ AU, and $n = 2$, we obtain:

$$J_o \simeq 3 \times 10^{51} \text{ g cm}^2\text{/s} \quad (7)$$

This value is larger than the present angular momentum of the whole planetary system by an order of magnitude and it is close to that of the angular momentum of the protoplanetary system before the loss of volatiles (*23–25*).

Thus, our second conclusion is that the main part of the present angular momentum of the solar system probably is not contained within the planets (as was considered before) but in the periphery of the system, namely the Oort cloud. In this case the total momentum of the solar system appears to be higher than was assumed by an order of magnitude when 98% of it was considered to be concentrated in the planetary system and 2% to be in the sun.

As is shown below, the distribution of mass and angular momentum in the solar system differs even more radically from previous assumptions if the Oort cloud is itself only a rarefied halo surrounding the core—a dense inner cometary reservoir. A possibility of the existence of the core was at first noticed by Oort in his pioneer study (*1*). The existence of a core was apparently at first argued theoretically by Hills (*8*), who determined its external boundary $r_e^{\text{core}} = 2 \times 10^4$ AU and internal one (supposed at the heliocentric distance $r_i^{\text{core}} = 3 \times 10^3$ AU). As mentioned above, the core is apparently flattened, its thickness seemingly increasing perpendicular to the ecliptic plane as $\Delta Z \sim a$ [see Marochnik *et al.* for the details (*9*)]. A review of observational arguments in favor of the core existence can be found in Weissman's paper (*10*). According to Hills (*8*), there should be the number of comets in the core equal to $N_{\text{core}} \simeq 200\ N_o$ to supply the halo (the Oort cloud) continuously by the core source in the process of halo exhaustion under action of closely passing stars. Therefore we assume that the number of comets is of the order of $N_{\text{core}} \simeq 10^2\ N_o$ [see also Weissman (*10*)]. At the same time, as was shown by Safronov (*26*), in his cosmogonic scenario, a mass up to 2.5 $M_\oplus$ could have been transported into the Oort cloud region from the planetary zone. More recent modeling by Fernandez and Ip (*27*) gives the mass that could be ejected from the Uranus-Neptune zone into the Oort cloud of the order of 9 to 28 $M_\oplus$. The Monte Carlo simulation of the identical situation by Shoemaker and Wolfe (*28*) shows a possibility to obtain M_o = 10 to 20 $M_\oplus$ and M_{core} = 100 to 200 $M_\oplus$. Recent simulation of the same problem by Duncan *et al.* (*29*) gave even smaller value for M_o. One can see that all these values are by one order less than M_o and M_{core} with respect to our estimates.

We believe, however, that the results of the numerical simulations described above on the contrary favor hypotheses that cometary nuclei formed in remote parts of the protosolar nebula, because the number of comets in the core (according to the numerical simulations) appears to be insufficient for supporting the halo (the Oort cloud) against exhaustion during the lifetime of the solar system (*8*). Cosmochemistry data also seem to maintain the idea that comets formed very far from the sun (see below). Therefore, assuming again $M_c \simeq M_H \simeq 3 \times 10^{17}$ g for a typical comet we find the core mass of the order $M_{\text{core}} \simeq 10^4\ M_\oplus = 0.03\ M_\odot$ located in the ring $r^{\text{core}} = r_e^{\text{core}} - r_i^{\text{core}}$.

As was shown by Hoyle (*23*), Kusaka *et al.* (*24*), and Weidenschilling (*25*), the mass of the protoplanetary nebula should be approximately $M_p^{\text{proto}} \simeq 0.01$ to $0.02\ M_\odot$ if the present planetary mass is added to the mass of the volatiles (up to restoration of solar composition). Therefore, the protosolar nebula appears to evolve in such a way that approximately equal masses were spent both to form the planets and to form the core. In this pattern the halo (the Oort cloud) was formed as a result of diffusion of some of the comets from the core (*8*).

Where might the cometary nuclei with total mass $M_{\text{core}} \simeq 0.03\ M_\odot$ form? Cosmochemical data undoubtedly show that the comets should form in any case at considerably remote heliocentric distance, if not in situ. The conditions of formation of the dust component and of the comet's nucleus itself may differ considerably. Hence, it is extremely important to choose reliable cosmo-thermometers to solve the problem of cometary nuclei genesis. From this viewpoint, carbon monoxide present in the comae of many comets seems to be the most promising cosmo-thermometer.

For instance, carbon monoxide was a major component observed at large heliocentric distances for comets Morehouse 1908 III, Humason 1962 VIII, and Kohoutek 1973 XII. The carbon monoxide content was the second highest (exceeded only by water) in comet Halley's coma.

There are good reasons to believe that the observed variations of the brightness of comets at appreciable heliocentric distances are associated with intense CO evaporation, accompanied with the formation of a halo of icy grains (*30*). Recent theoretical estimates (*31*) and experimental work (*32*) confirm the viewpoint according to which carbon monoxide (or its clathrate hydrates) should be one of the basic components of cometary ices. The CO clathrate formation temperature corresponding to the Uranus-Neptune zone requires too high a partial pressure of CO in the protoplanetary nebula (*30*).

Thus we are justified in saying that the temperature at which cometary ice (and, hence, cometary nuclei) form is within 25 K; and this immediately pushes the zone where comets are formed beyond 60 to 100 AU. The question should be always kept in mind whether CO is truly a parent molecule or whether there may exist a certain short-lived molecule whose disintegration in a cometary coma results in CO formation. Most obviously, a high CO content in the comae of different comets suggests that it is indeed CO that is a parent molecule, though it is possible that some more CO molecules are generated from the organic component of dust (*32*).

As we noted above, the simplest dynamical estimates also give evidence in favor of the hypothesis of comet formation in the remote periphery of the protosolar nebula. It is difficult to assume that a widely accepted alternative mechanism, in which a comet is formed in the Uranus-Neptune zone and is subsequently ejected to the periphery of the protosolar nebula as a result of gravitational perturbations, could be sufficiently effective because the masses of the protoplanetary system and of the core are of the same order. Even if the core hypothesis is not confirmed in the future, as was noted above, the mass of the Oort cloud alone appears to be too great for gravitational perturbations of the planets to be capable of ejecting to the periphery such an amount of material.

The above considerations argue in favor of the models in which the comets are formed at more remote heliocentric distances either in situ (*14, 15*) or at the distances of several hundred astronomical units with a subsequent displacement (for example, caused by a loss of mass from the nebula) to the region $r \simeq 2 \times 10^3$ AU (*16*). As was shown by Biermann and Michel (*14*) and Cameron (*17*), a formation of solid bodies with the masses 10^{18} g (that is, with the masses of the order of M_c, M_H) is possible within the framework of their models.

If the cometary nuclei were formed in the remote regions of the protosolar nebula, in contrast to the concept that they were isotropically (or quasi-isotropically) ejected to the periphery of the solar system by gravitational perturbations of the planets after formation, then the core and halo should possess a great angular momentum because the cometary nuclei arising in a rotating protosolar disk must conserve (to within an order of magnitude) the initial angular momentum of the materials from which they were formed.

Let us estimate the angular momentum of the core. Because the core is nonthermalized, the question of how the eccentricities of the comets are distributed requires special consideration. Let us use Eqs. 2 and 4, which give

$$J_{\text{core}} = \frac{3}{2} J_o \beta (1 - e^2)^{1/2} \qquad (8)$$

Here $\beta = N_{\text{core}}/N_o$ and it is assumed that the comet distribution over semimajor axes in the Oort cloud and the core are the same and identical to Eq. 4 [see, for example, the paper by Hills (*8*)]. Being interested in the order of magnitude only, let us consider two extreme cases: (i) all comets in the core move along circular Keplerian orbits ($e = 0$) and (ii) all comets in the core move along strongly eccentric quasi-parabolic orbits ($e \lesssim 1$). In the case of $e = 0$, assuming $\beta = 10^2$, $a_{\text{min}} = 2 \times 10^3$ AU, $a_{\text{max}} = 2 \times 10^4$ AU, we get from Eq. 8

$$J_{\text{core}} \simeq 2 \times 10^{53} \text{ g cm}^2/\text{s} \qquad (9)$$

The estimate Eq. 9 depends on the assumption of formation of comets in situ (for estimating the momentum, the present value a_{min} is used). If formation of the cometary nuclei took place, for example, according to the Cameron model (*33*), then $a_{\text{min}} \simeq 300$ AU, $a_{\text{max}} \simeq 600$ AU. Substituting these values in Eq. 8 gives

$$J_{\text{core}}^{\text{Cameron}} \simeq 5 \times 10^{52} \text{ g cm}^2/\text{s} \qquad (10)$$

In the case of $e < 1$, Eq. 8 should be rewritten in terms of the perihelion distance $q = a(1 - e)$, that is, by means of the formula

$$a_{\text{min}}(1 - e^2) \simeq 2q_{\text{min}} \qquad (11)$$

where q_{min} is the perihelion distance of comets in the core that have the minimum semimajor axes a_{min}. Substituting $q_{\text{min}} \simeq 100$ AU, for example, and including Eq. 11, we obtain from Eq. 8

$$J_{\text{core}} \simeq 5.7 \times 10^{52} \text{ g cm}^2/\text{s} \qquad (12)$$

Thus, the following estimate can be written for the angular momentum of the core:

$$5 \times 10^{52} \frac{\text{g cm}^2}{\text{s}} \lesssim J_{\text{core}} \left(\frac{M_{\text{core}}}{10^4 M_\oplus} \right)^{-1} \lesssim 2 \times 10^{53} \frac{\text{g cm}^2}{\text{s}} \qquad (13)$$

Taking into account all of the uncertainties in evaluating inequality 13 (the mass of "average" comet in the core, its internal boundary location, the zone of comet formation in the protosolar nebula, and so on), the coefficients of the order of unity should not be considered to be of significance.

Thus, the following pattern of momentum distribution in the solar system arises. The present angular momentum of the planetary system is close to the value $J_p = 3 \times 10^{50}$ g cm²/s. The planetary system, with volatiles added up to a value that restores the solar composition, had the angular momentum $J_p^{\text{proto}} \simeq 3$ to 5×10^{51} g cm²/s (*23–25*), which is nearly identical to the present Oort cloud.

According to expression 13, the angular momentum of the core is one or two orders of magnitude more than the angular momentum of the halo and two or three orders of magnitude higher than the present angular momentum of the planetary system. Its value, however, does not exceed the limit of the upper estimate of a possible momentum of the protosolar nebula. Actually, the spherical volume of the interstellar medium with mass $M \simeq M_\odot$ has the angular momentum $J_G \simeq 10^{54}$ g cm²/s (*16*) owing to galaxy rotation and the angular momentum of typical galactic molecular cloud is such that recalculating into the mass $M \simeq M_\odot$ we have (*34*)

$$J_{\text{MC}} \simeq 10^{53} \text{ to } 10^{55} \text{ g cm}^2/\text{s} \qquad (14)$$

This large an unseen mass in the form of cometary nuclei in the region $r^{\text{core}} = 3 \times 10^3$ to 2×10^4 AU does not contradict the estimate of the extreme possible mass of the core made by Hills (*8*); the same order of mass is obtained for the part of the protosolar nebula in Cameron's model (*17*) that is spent, for example, in forming the comets in the nebula's distant subfragments.

It was Weissman who in 1986 (*35*) called attention to the importance of the mass reestimation of the Oort cloud for the problem of the origin of the solar system. We understand that in our report we used some upper estimates for values of the number of comets in the core. Nevertheless, the decreasing of comet population in the core even by a factor of 10 does not change the dramatic situation with the distribution of the angular momentum in the solar system (see expression 13).

Therefore, in the framework of the above hypothesis we can imagine the present structure of the solar system as follows. There is the planetary system with mass $M_p \simeq 448$ $M_\oplus$, angular momentum $J_p \simeq 3 \times 10^{50}$ g cm²/s, and radius about 40 AU; then there is a void up to the distances about 3×10^3

AU; out of the void the giant unseen mass $M_{core} \simeq 10^4\ M_\oplus$ is situated with the angular momentum of the order of 10^{52} to 10^{53} g cm^2/s in the form of cometary nuclei up to the distances about 2×10^4; and then the halo (the Oort cloud) is situated with the mass $M_o \simeq 100\ M_\oplus$ and the angular momentum $J_o \simeq 3 \times 10^{51}$ g cm^2/s.

Let us finally emphasize that the structure of the solar system described above does not contradict, apparently, the IRAS data for observations of infrared excesses in the stars in the solar neighborhood of the galaxy (*9*).

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36. We thank Drs. V. Moroz and V. Strelnytsky for discussions. We also especially thank Dr. P. Weissman for helpful remarks and discussion.

29 March 1988; accepted 8 August 1988

Observations of the Nighttime Abundance of OClO in the Winter Stratosphere Above Thule, Greenland

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Observations at Thule, Greenland, that made use of direct light from the moon on 2, 3, 4, 5, and 7 February 1988 revealed nighttime chlorine dioxide (OClO) abundances that were less than those obtained in Antarctica by about a factor of 5, but that exceeded model predictions based on homogeneous (gas-phase) photochemistry by about a factor of 10. The observed time scale for the formation of OClO after sunset strongly supports the current understanding of the diurnal chemistry of OClO. These data suggest that heterogeneous (surface) reactions due to polar stratospheric clouds can occur in the Arctic, providing a mechanism for possible Arctic ozone depletion.

The column content of ozone (O_3) over Antarctica during the spring has decreased by ~50% during the past decade (*1*). Several studies (*2, 3*) suggested that this depletion at that particular season and latitude could be related to the enhanced abundance of polar stratospheric clouds (PSCs) there, in association with prevailing extreme low temperatures. The PSCs form abruptly when stratospheric temperatures drop below about −80°C (*4*), and play a critical role by providing an ice surface on which halogen compounds can engage in heterogeneous reactions (*5*), such as

$$HCl\ (s) + ClONO_2\ (g) \rightarrow Cl_2\ (g) + HNO_3\ (s) \qquad (1)$$

or

$$H_2O\ (s) + ClONO_2\ (g) \rightarrow HOCl\ (g) + HNO_3\ (s) \qquad (2)$$

The net effect of these reactions is to liberate reactive chlorine (ClO_x) from the relatively inert chlorine reservoir species, HCl and $ClONO_2$, and thus enhance the potential for halogen chemistry to catalytically destroy O_3 over the height range where the PSCs are located [roughly 10 to 25 km as shown, for example, in (*4*)].

The chemistry of halogen species in the lower stratosphere is closely coupled to that of reactive nitrogen species (NO_x) because of the rapid formation of nitrates, specifically $ClONO_2$ and $BrONO_2$. For reactions such as 1 and 2 to effectively enhance the net abundance of ClO_x radicals, the lower stratospheric NO_x content must be greatly reduced so that reformation of $ClONO_2$ does not limit their accumulation (*2, 3*). Reactions 1 and 2 both produce reactive ClO_x radicals at the expense of their long-lived reservoirs and convert reactive nitrogen to the much less reactive species, HNO_3. Additional heterogeneous reactions involving N_2O_5 (*5*) and the direct condensation of HNO_3 at temperatures below about −80°C (*6*) are likely to further inhibit the gas-phase abundance of NO_x species, so that PSC chemistry produces an atmosphere rich in ClO_x radicals and depleted in NO_x radicals.

Sunlight is also involved in Antarctic O_3 depletion. For example, the Cl_2 produced in reaction 1 must first photolyze to form two chlorine atoms, which then react rapidly with O_3 and initiate its catalytic destruction (*3, 7*). Thus the depletion of Antarctic O_3 is believed to involve the following primary elements: PSC formation at temperatures below about −80°C, subsequent surface chemistry that enhances chlorine free radicals and suppresses reactive nitrogen species, and fast photochemical depletion processes that require sunlight (*2, 3, 5, 7*).

Measurements of the stratospheric composition in Antarctic spring have revealed that the photochemistry of this region must be profoundly different from that found elsewhere, in a manner consistent with the identification of the ozone hole as a largely chlorine-induced phenomenon (although

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