THE DISTRIBUTION OF HELIUM AND ATOMIC OXYGEN

IN THE LOWER EXOSPHERE

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Presented at the 48th Annual Meeting of the
American Geophysical Union

Washington, D.C.
April 17-20, 1967 [redacted]

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ABSTRACT

The authors recently reported that maximum atmospheric densities measured by the Explorer XIX and XXIV satellites occurred in the early afternoon in the winter hemisphere, that is, the hemisphere opposite the equator from the sun. They referred to this density peak as the winter bulge. Previously, it was generally assumed that maximum densities at these altitudes (550 km to 750 km), where atomic oxygen and helium are the primary constituents, would occur in the early afternoon in the summer hemisphere. In the present paper, drag data from the Explorer IX, XIX, and XXIV satellites have been used to obtain a more complete picture of the winter bulge. These data cover the altitude range 390 km to 880 km and the time interval between 1961 and 1966. A correlation is found between the bulge latitude and the inferred helium to atomic oxygen ratio. This correlation indicates that the winter bulge is the result of a high latitude winter helium bulge. Superimposed upon this helium bulge is a near-equatorial summer oxygen bulge. The winter helium bulge occurs in the early afternoon and migrates latitudinally in the opposite sense of the sun from high latitudes in the hemisphere opposite the sun at the solstices to near the equator at the equinoxes. A study of drag data from the Echo II satellite confirms the high latitude winter helium bulge. The abundance of helium at high latitudes in the winter is not attributed to higher exospheric temperatures but to a seasonal variation in helium concentration at 120 km which may be related to the level at which diffusive separation of helium begins.

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INTRODUCTION

Peak atmospheric densities occur at satellite altitudes at approximately 2:00 every afternoon. This region of peak densities is termed the diurnal bulge. Although the local solar time of the diurnal bulge is generally agreed upon, the latitudinal migrations of the bulge center are still in question. Originally, peak atmospheric densities and exospheric temperatures were assumed to follow the latitudinal migrations of the sun (ref. 1). More recently, this picture has changed after analysis of drag data from the Air Density Explorer satellites. Jacchia and Slowey (ref. 2) found they could obtain a better prediction rule by assuming the diurnal bulge remained on the equator rather than following the latitude of the sun. Keating and Prior (ref. 3) analyzed data from the latest two Air Density Explorers, Explorer XIX and XXIV, during a period of low solar activity between the altitudes of 550 km and 750 km. They found the diurnal bulge occurred in the winter hemisphere, that is, the hemisphere opposite the equator from the sun. The authors referred to this density peak as a "winter bulge." Using the winter bulge gives better agreement with observations than the equatorial bulge of reference 2 or the summer bulge of reference 1. The present study was undertaken to determine over what altitude range and/or range of solar activity a winter bulge existed. Densities inferred from the atmospheric drag upon satellites Explorer IX, XIX, XXIV, and Echo II were used for determining the latitudinal variations of the diurnal bulge over the years 1961 to 1966 and over the altitude ranges of 390 km to 1130 km. A shift of bulge position with altitude appears to be related to the diffusive separation of atmospheric constituents in the exosphere. As a result, the study provided new insight into the distribution of the major constituents of the lower exosphere, atomic oxygen and helium. The high-altitude winter bulge appears to be the result of an increased helium concentration in the winter hemisphere while the observed summer bulge of atomic oxygen may coincide with high exospheric temperatures.

DENSITY DATA

Four low mass-area ratio satellites were used in this study of the latitudinal variations of the diurnal bulge in the exosphere. These satellites were chosen due to their sensitivity to the drag environment. Explorer IX, XIX, and XXIV were each 12-foot-diameter (3.66 m) Air Density Explorer satellites which weighed less than 10 kilograms. Echo II is a 135-foot-diameter (41.1 m) sphere which weighed 256 kilograms. Explorer IX was launched in February 1961 and reentered in 1964. Densities near its perigee point were deduced from its energy decay. Its perigee point precessed in such a fashion that it was in near resonance with the relative motion of the sun. As a result, densities were measured near the hour angle of the diurnal bulge throughout the satellite lifetime. Thus, it was a valuable tool for measuring variations in bulge position. In this study, Explorer IX measurements between the latitudes of ±39° were made over the altitude interval 390 km to 880 km. The Explorer XIX and XXIV satellites were placed into near-polar orbits. As a result, although their perigees do not always remain close to the diurnal bulge, they can adequately measure latitudinal variations of atmospheric density in the exosphere. The Explorer XIX and XXIV data studied include recent data not included in the study of reference 3. Explorer XIX data cover the latitudes ±79° and the altitude interval 630 km to 750 km. Explorer XXIV data cover the latitudes ±81° and the altitude interval 550 km to 660 km. The Echo II density data are taken from reference 4. It has been normalized to an altitude of 1130 km, and covers the latitude range ±82°. The Echo II satellite orbit is sometimes so circular that the position of the density measurement is difficult to pinpoint. Consequently, the period of measurements when the eccentricity was less than 0.015 has been deleted. This covers the interval July 28, 1964, through January 5, 1965.

The methods developed for the determination of densities from the Air Density Explorer satellites have been described in detail by Keating, Mullins, and others (refs. 5 and 6). The effects of atmospheric drag are deduced by subtracting energy changes due to radiation forces from the total energy decay. Radiation forces were evaluated from reflectance measurements of the satellite material (refs. 6 and 7). The assumed drag coefficient increases with perigee altitude. The density at perigee is evaluated by matching the observed energy decay due to drag with the energy losses obtained when the satellite is moving through the rotating spring/fall atmosphere of reference 8. This model atmosphere has a different density profile for each exospheric temperature, and is nearly identical with the static diffusion models of reference 1. In order to minimize errors in atmospheric density due to inaccuracies in the assumed atmospheric model, the density is then evaluated at an altitude between 1/2 and $\sqrt{3}/2$ density scale heights above perigee, depending on the value of the density scale height and its rate of variation (ref. 6). This is similar to the technique employed in reference 9.

THE DIURNAL BULGE

The summer bulge model of Jacchia (ref. 1), the equatorial bulge of Jacchia and Slowey (ref. 2), and the winter bulge of Keating and Prior (ref. 3) can all be obtained by varying the parameter B in the following expression given by Keating and Prior in equation (4) of reference 10:

$$T = T_o\left[1 + 0.28 \sin^m\theta' + 0.28(\cos^m\eta' - \sin^m\theta')\cos^{2.5}\left(\frac{\tau}{2}\right)\right] \qquad (1)$$

where

$\eta' = \frac{1}{2}\left|\delta_P - B\delta_S\right|$, deg

$\theta' = \frac{1}{2}\left|\delta_P + B\delta_S\right|$, deg

$\tau = H - 45^{\circ} + 12^{\circ} \sin(H + 45^{\circ})$, deg $\qquad -\pi \leq \tau \leq \pi$

H = hour angle of sun, deg

δ_P = declination or latitude of density point, deg

δ_S = declination or latitude of sun, deg

T_O = minimum exospheric temperature, $^{\circ}K$

$\delta_B = B\delta_S$ = declination or latitude of diurnal bulge center, deg

B = constant

m = coefficient

T = exospheric temperature at H, δ_P before geomagnetic activity correction, $^{\circ}K$

After calculating the exospheric temperature, the atmospheric density can be determined at any altitude by entering the spring/fall tables in the U.S. Standard Atmosphere Supplements, 1966 (ref. 8) or the nearly equivalent tables of reference 1. The models give density as a function of altitude for any exospheric temperature. Actually, exospheric temperatures are deduced from the models and are therefore no more valid than the assumptions made to generate the models such as invariant boundary conditions at 120 km. However, inferred exospheric temperature is a useful parameter for predicting densities over a wide range of altitudes, and gives some indication of the range of temperatures in the lower exosphere.

A study of the parameter B of equation (1) gives insight into the nature of the latitudinal migrations of the diurnal bulge. Since the latitude of the bulge center is given by B times the latitude of the sun, a negative B indicates a diurnal bulge remaining in the winter hemisphere while a positive B indicates a diurnal bulge in the summer hemisphere. Shown in figure 1 is the variation of bulge position as a function of latitude and time of year for different values of B. For each value of B, the local solar time of the bulge is constrained in equation (1) to approximately 1400. The diurnal bulge of reference 1, which follows the latitudinal migrations of the sun, corresponds to $B = +1$ and $m = 2.5$. The equatorial bulge of reference 2 corresponds to $B = 0$ and $m = 1.5$. The winter bulge of reference 3, which gives even lower residuals than the first two models, corresponds to $B = -1$ and $m = 1$. The constant m indicates how rapidly density drops off latitudinally from the bulge center. A low value of m such as $m = 1$ indicates atmospheric density in the daytime drops more slowly from the bulge center with latitude than with hour angle.

In previous studies, a constant value of B has been assumed over the entire range of satellite data. It was therefore undertaken to determine whether the assumption of constant B was valid; and if B did vary, what parameters would affect it. Density data from the Air Density Explorer satellites and Echo II satellites were divided in such a fashion as to give representative samples of latitudinal variations. For example, Explorer IX data were divided into approximately 5-month intervals corresponding to two revolutions of the perigee point. Thus, the range of latitudes was sampled four times in each interval.

Densities were predicted for each observation, taking into account the effects of geomagnetic activity, solar activity, and the semiannual variation given in the U.S. Standard Atmosphere Supplements, 1966 (ref. 8). As a result, the minimum exospheric temperature on any date was assumed to be given by the following expression:

$$T_o = 362^\circ + \left[3.60^\circ \bar{F}_{10.7} + 1.8^\circ\left(F_{10.7} - \bar{F}_{10.7}\right)\right]$$
$$+ 1.0^\circ\left[0.37 + 0.14 \sin 2\pi\left(\frac{d - 151}{365}\right)\right]\bar{F}_{10.7} \sin 4\pi\left(\frac{d - 59}{365}\right) \tag{2}$$

where

$F_{10.7}$ = 10.7-cm flux from sun divided by 10^{-22} watts/m^2/cycles/sec

$\bar{F}_{10.7}$ = 10.7-cm flux from sun averaged over three solar rotations divided by 10^{-22} watts/m^2/cycles/sec

d = number of days counted from January 1

The minimum exospheric temperature T_o was then substituted into equation (1), m was set equal to 1, and B was set equal to values ranging from -3.9 to 3.9. The increase in temperature related to geomagnetic activity was determined using the following expression (ref. 8):

$$T' = T + 1.0^\circ(a_p) + 100^\circ\left[1 - \exp(-0.08\ a_p)\right] \tag{3}$$

where

T' = corrected exospheric temperature, $^\circ K$

a_p = geomagnetic planetary amplitude

The spring/fall models of reference 8 were generated up to 1130 km in order to obtain predictions of Echo II densities. The models indicate that for the Echo II satellite, helium drag is generally 10 times as high as hydrogen drag.

For each observed density of the four satellites, a corresponding predicted density was obtained using equations (1), (2), and (3), and the spring/fall models of reference 8. For each value of B in equation (1), a standard deviation between predicted and observed densities was obtained for each interval of data points. The values of B giving the lowest standard deviation for each data set are tabulated in table 1.

The first two columns of table 1 give the satellite and data interval of each data set studied. The second two columns give the average altitude and average inferred temperature of each set. The last column, $\log_{10}[n(He)/n(O)]$, is determined knowing the average altitude and average temperature of each data set and using the models of reference 8. The variation in the helium-to-atomic-oxygen ratio is due to the diffusive separation of constitutents in the exosphere. Standard deviations of $\log_{10}$ of the atmospheric density for individual data sets averaged about 0.08. Mean densities were generally slightly greater than the models above 600 km, and less than the models below 600 km.

Shown in figure 2 is the variation of B with $\log_{10}[n(He)/n(O)]$ corresponding to the tabulation in table 1. On the left of the figure, atomic oxygen is the primary constituent, while on the right, helium is the primary constituent. Above $\log_{10}[n(He)/n(O)]$ of 0.4, all 11 data points give negative B and therefore indicate a winter density bulge. Each of these data points represents many months of satellite data. The remaining four data points, in an atmosphere primarily composed of atomic oxygen, indicate a summer density bulge. There is a general trend for the value of B to shift from positive in an atomic oxygen atmosphere to negative in a helium atmosphere. Remembering that positive B indicates a summer bulge and negative B indicates a winter bulge, it is apparent that the observed diurnal bulge shifts hemispheres depending upon which constituent is predominant. It is also apparent that a constant B model such as the equatorial bulge of reference 2 (B = 0) does not adequately describe the location of the diurnal bulge center in the lower exosphere.

The shift in bulge latitude can be understood by envisioning two bulges existing simultaneously, a winter helium bulge occurring at high latitudes in the winter hemisphere, and a summer oxygen bulge occurring at low latitudes in the summer hemisphere. This concept is pictured schematically in figure 3. This diagram is not intended to show the shape or the altitudinal variations in the bulges. The sun is shown near summer solstice in the Northern Hemisphere. Atomic oxygen is shown to peak at low latitudes on the sun side of the equator. Helium peaks at high latitudes in the hemisphere opposite the sun. As the sun migrates latitudinally down to the equator, so do both bulges. Then the sun, followed by the atomic oxygen bulge, moves into the Southern Hemisphere and the helium bulge shifts into the Northern Hemisphere. With increasing altitude, helium replaces atomic oxygen as the primary constituent, and the region of maximum total atmospheric densities shifts from the summer hemisphere to the winter hemisphere. It also follows that with increasing solar activity and exospheric temperatures, atomic oxygen predominates to greater altitudes, and the summer bulge will be observed at greater altitudes.

Empirical expressions have been developed for the atomic oxygen bulge and the helium bulge. These expressions are in terms of a virtual exospheric temperature which may in turn be converted to atmospheric density using the static diffusion models of reference 8. The helium bulge is considered to be the result of a seasonal variation in the boundary conditions given for 120 km. Thus, the exospheric temperatures for helium are considered virtual since they are based on invariant boundary conditions. The distribution of helium is predicted by setting the B of equation (1) equal to -3.0, and m equal to +1. The atomic oxygen distribution is predicted by setting B equal to +0.25, and m equal to +1.

A sample calculation is made to show how the number densities of helium and atomic oxygen can be predicted at any position in the lower exosphere and how exospheric densities can be calculated. Determine the number densities of atomic oxygen and helium for July 25, 1965, for an altitude of 700 km, an hour angle of the sun of 60°, and a latitude of 45°. First, calculate T_o from equation (2) setting $F_{10.7} = 70$, $\bar{F}_{10.7} = 75$, and $d = 205$. It is found that $T_o = 589^{\circ}$ K. Next, calculate the virtual exospheric temperature of atomic oxygen from equations (1) and (3) setting $T_o = 589^{\circ}$ K, $H = 60^{\circ}$, $\delta_P = 45^{\circ}$, $\delta_S = 20^{\circ}$, $B = +0.25$, $m = 1$, and $a_P = 6$. Finally, determine the number density of atomic oxygen entering the tables of reference 8 at $T' = 782^{\circ}$ K and altitude equal to 700 km. The number density of atomic oxygen equals 7.72×10^{4} cm^{-3}. To determine the virtual temperature of helium setting $T_o = 589^{\circ}$ K, $H = 60^{\circ}$, $\delta_P = 45^{\circ}$, $\delta_S = 20^{\circ}$, $B = -3.0$, and $m = 1$, in equation (1), it is found that $T = 684^{\circ}$ K. Setting $a_P = 6$ in equation (3), $T' = 728^{\circ}$ K. Entering the tables of reference 8 at $T' = 728^{\circ}$ K and altitude equal to 700 km, the number density of helium equals 6.70×10^{5} cm^{-3}. Neglecting the minor contributions of other constituents, this gives a total density of 6.50×10^{-18} g/cm^{3}.

DISCUSSION

Rather than a seasonally dependent unknown heat source near the boundary of the exosphere, it is expected that the winter bulge is the result of a seasonal variation of helium concentration in the lower thermosphere. This seasonal variation may be related to a shift in the effective altitude at which diffusive separation of helium begins. A slight increase in this altitude, possibly related to increased turbulence, may sharply reduce helium concentrations in the upper thermosphere and exosphere (ref. 11). There is also an indication that total densities are higher and temperatures lower at 120 km in winter than in the summer (ref. 8). For a heavy constituent such as molecular nitrogen, this seasonal variation can be dwarfed at greater altitudes by the effects of high summer temperatures. For a lighter constituent such as helium, which is not as strongly affected by temperature, such a variation could extend into the exosphere. The low latitude summer oxygen bulge is expected to correspond to high exospheric temperatures. The oxygen bulge given by the model is closer to the equator than the subsolar point. This may result from the ion drag effects upon the neutral atmosphere suggested by Jacchia and Slowey in reference 2 or from seasonal variations at 120 km indicated by Champion (refs. 8 and 12).

CONCLUSIONS

A study was performed to determine the latitudinal migrations of the diurnal density bulge of neutral constituents in the lower exosphere. This study was based on satellite drag data in the altitude range 390 km to 1130 km and the time period 1961 to 1966. The following may be concluded:

1. At altitudes where atomic oxygen predominates, the diurnal bulge remains at low latitudes in the summer hemisphere, that is, hemisphere on sun side of equator.

2. The diurnal bulge remains in the winter hemisphere at greater altitudes where helium replaces atomic oxygen as the major constituent. The winter bulge migrates up to high latitudes near the time of the solstices and down to the equator near the time of the equinoxes.

3. The observed phenomena appear to result from the simultaneous existence of a high latitude winter helium bulge and a low latitude summer atomic oxygen bulge. As a result, a simple two-bulge model has been developed to describe the lower exosphere, and can be used to predict atmospheric densities.

4. With increasing altitude, as helium replaces atomic oxygen as the primary constituent, the diurnal bulge shifts from the summer hemisphere to the winter hemisphere. With increasing solar activity and exospheric temperature, the peak altitude where atomic oxygen predominates will increase, and it is expected that the altitude where the bulge shifts hemispheres will increase.

5. The high latitude winter helium bulge is expected to be caused by a seasonal variation of helium concentration in the lower thermosphere which extends into the exosphere. This seasonal variation may be related to a slight shift in the effective altitude at which diffusive separation of helium begins.

6. The atomic oxygen bulge is expected to closely correspond to peak exospheric temperature.

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TABLE 1.- VARIATION OF THE PARAMETER B WITH ATMOSPHERIC PROPERTIES FOR EACH DATA INTERVAL

Satellite	Time interval	Average altitude, km	Average inferred temperature, $^{\circ}K$	B	$\log_{10}\left[\frac{n(He)}{n(O)}\right]$
Explorer IX	2/21/61-7/19/61	744	964	-0.7	+0.53
Explorer IX	7/25/61-12/22/61	813	996	-1.7	+.74
Explorer IX	12/28/61-5/27/62	834	970	-2.5	+.97
Explorer IX	6/2/62-10/30/62	783	945	-1.1	+.79
Explorer IX	11/5/62-4/4/63	672	904	+.7	+.36
Explorer IX	4/10/63-9/7/63	547	834	+.9	-.14
Explorer IX	9/13/63-1/21/64	428	817	+.7	-.88
Explorer XIX	12/24.5/63-12/29/64	663	815	-1.1	+.65
Explorer XIX	1/13/65-1/6.5/66	692	832	-2.5	+.74
Explorer XIX	1/21/66-7/28.5/66	718	911	-.3	+.60
Explorer XXIV	12/9.5/64-11/3/65	597	802	+.1	+.30
Explorer XXIV	11/15.5/65-7/26/66	638	831	-.5	+.41
Echo II	2/13/64-7/14/64	1130	848	-2.4	+3.09
Echo II	1/12/65-5/25/65	1130	780	-2.6	+3.63
Echo II	6/1/65-10/19/65	1130	823	-3.3	+3.28

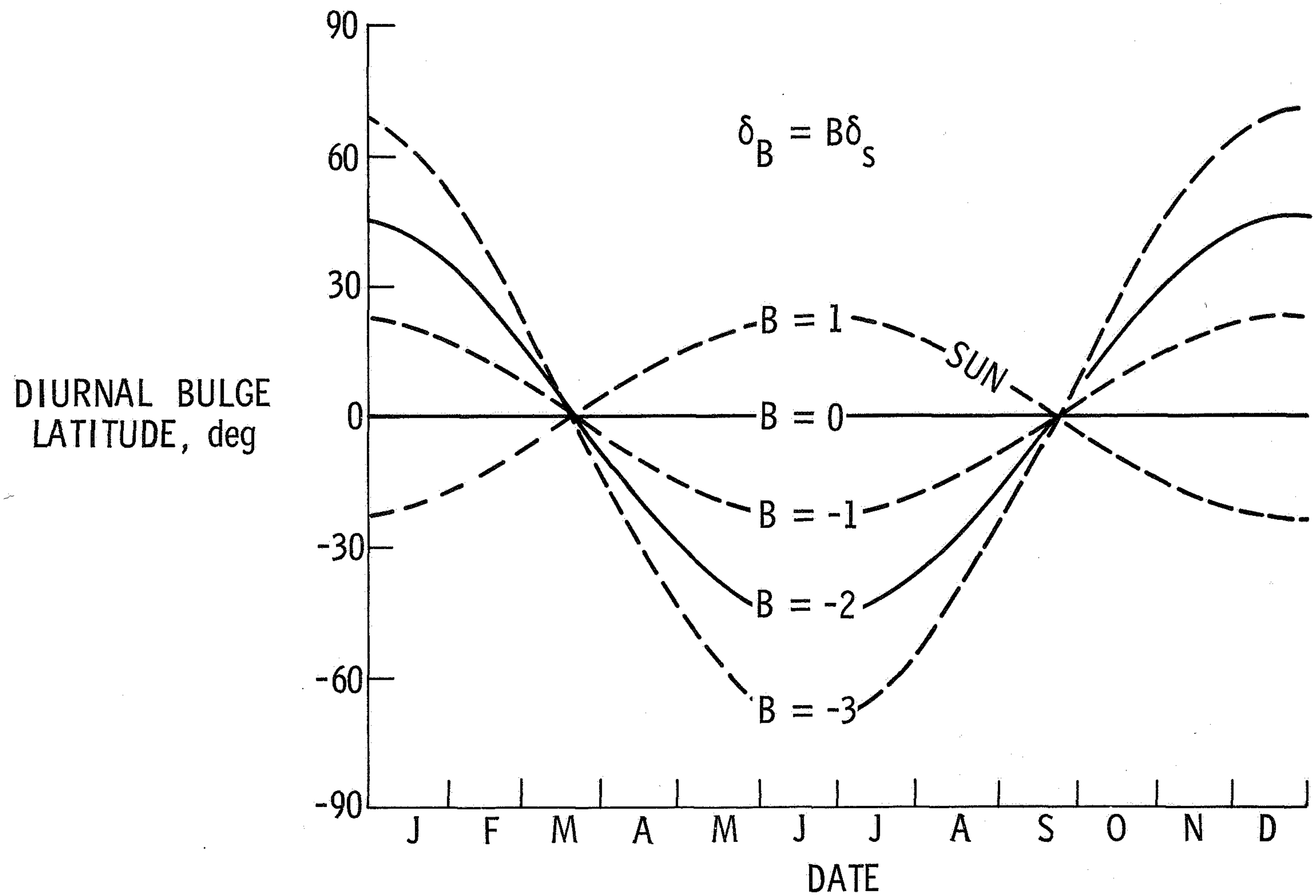

Figure 1.- Latitude of diurnal bulge center as a function of date for constant values of B.

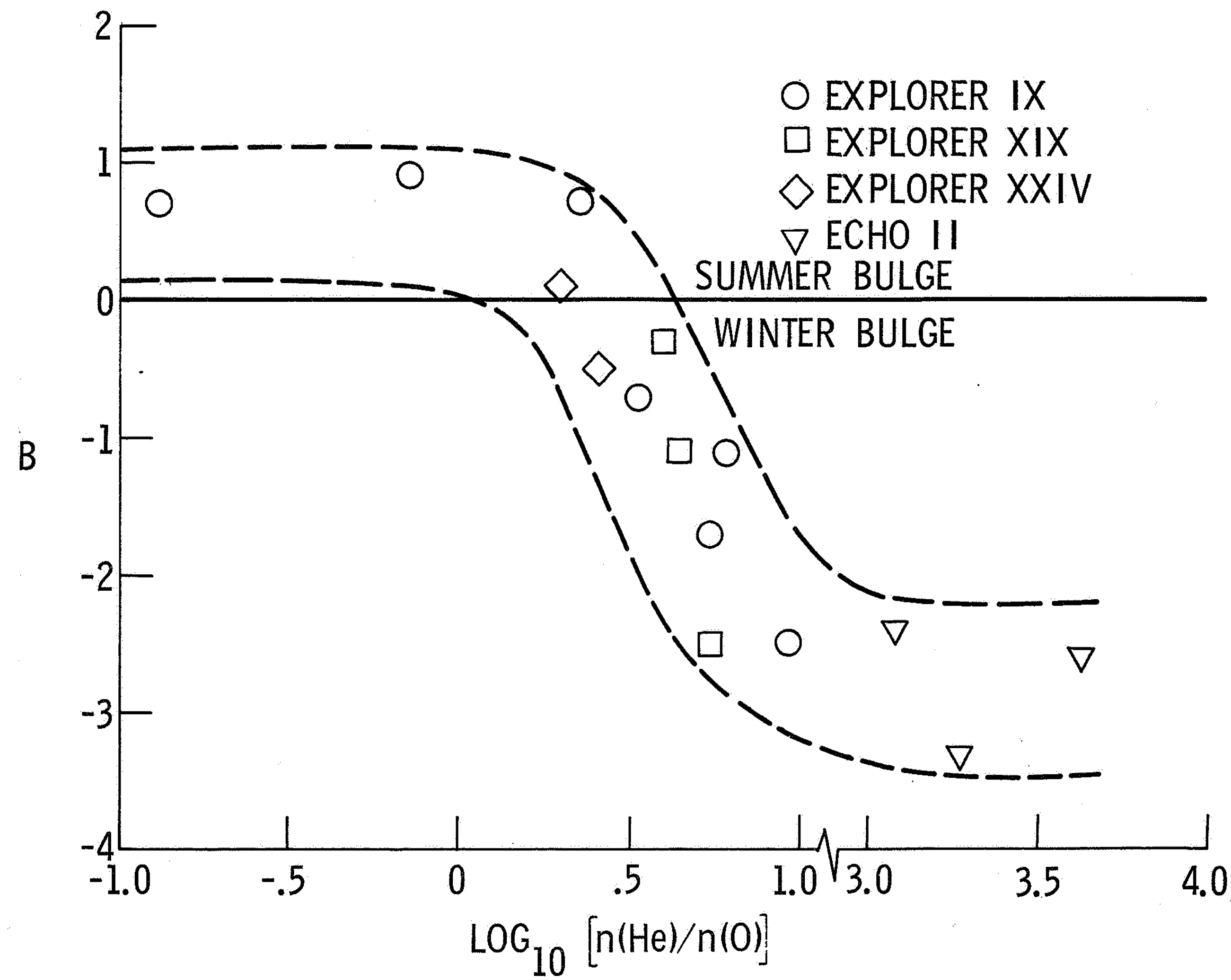

Figure 2.- Relationship between observed values of parameter B, which gives latitudinal-seasonal variation of diurnal bulge position, and relative concentrations of helium to atomic oxygen.

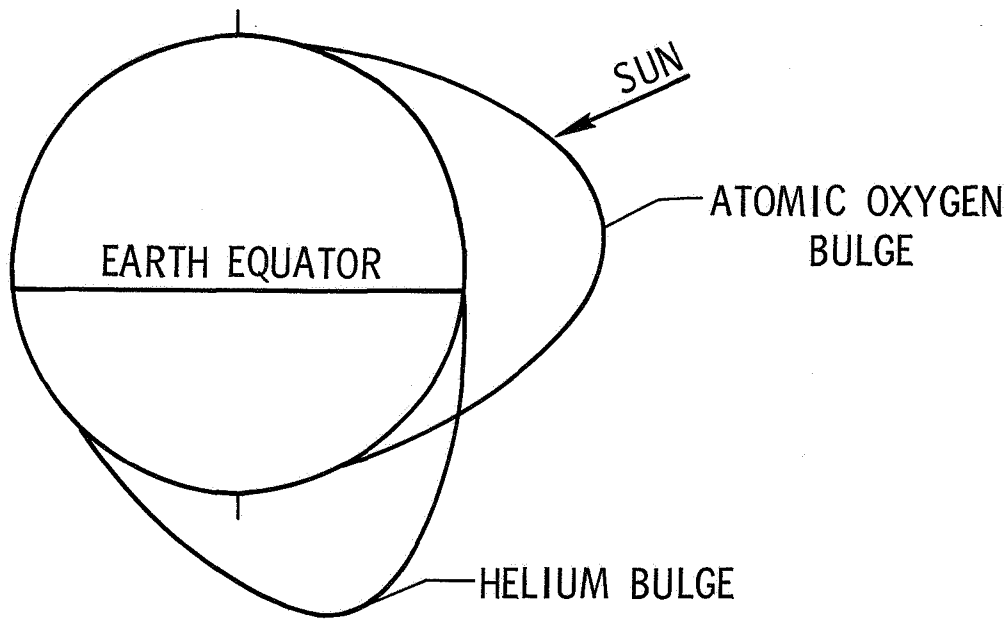

Figure 3.- Schematic diagram of orientation of helium and atomic oxygen bulges.

NASA-Langley, 1967