PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Comparison of Air Densities Obtained from Orbital Decay and Instruments

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Phil. Trans. R. Soc. Lond. A 1967 **262**, 172-184
doi: 10.1098/rsta.1967.0044

Comparison of air densities obtained from orbital decay and instruments

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Methods for determining upper-atmosphere density are briefly reviewed. Values of air density derived from orbital decay are compared with those obtained from instruments and shown to be systematically higher. The difference is too large to be due entirely to errors in the drag-derived values and cannot be explained at present if the absolute accuracy claimed for the gauges is realistic.

1. Introduction

Over the past few years a great deal has been learnt about the Earth's upper atmosphere, chiefly by evaluating air density from the changes in the orbital periods of satellites. Most of the density values refer to heights between 150 and 700 km, although there have been a few studies of densities at greater heights. The upper atmosphere is under strong solar control; the highest values of density occur when the Sun is most active, and there is an appreciable day-to-night variation. The upper atmosphere also varies in unison with geomagnetic activity and exhibits a semi-annual variation. These variations have been reviewed by Jacchia (1967, this volume, p. 157). The change in orbital period gives only the air density: the other atmospheric properties have to be inferred by fitting an acceptable theoretical model to the density data.

Before 1963 almost the only other data on the neutral atmosphere above 150 km consisted of a small number of measurements made by instruments carried by sounding rockets. In contrast to the drag data, which provide almost continuous values of density at a variety of heights and are reasonably well distributed around the globe, the early rocket experiments only provided sporadic information on density, temperature and composition at heights of 100 to 220 km over specific locations. A few measurements of atmospheric properties were made using instruments aboard Sputnik 3 (1958 $\delta 2$) (Mikhnevich, Danilin, Repnev & Sokolov 1959), but it was not until the launching of the aeronomy satellite Explorer 17 (1963–09 A) in April 1963 that instrument techniques were given a degree of coverage comparable with the drag data. Rocket flights are now providing an increasing amount of information at heights between 150 and 300 km, a region of the atmosphere that has been studied recently at the Royal Aircraft Establishment using the orbits of Cosmos rockets (King-Hele & Quinn 1966).

Comparison of atmospheric properties measured using instruments aboard Explorer 17 with those derived from drag studies has shown that there are systematic differences which exceed the combined uncertainties claimed for the two methods (Newton, Horowitz & Priester 1964; Cook 1965*a*). It is the purpose of the present paper to briefly review the methods employed in the determination of upper-atmosphere density and to discuss the discrepancies.

2. METHODS OF DETERMINING UPPER-ATMOSPHERE DENSITY

2·1. *Drag studies*

The simplest method of determining air density at heights between 150 and 1200 km is to use the satellite itself as the measuring instrument. Provided the mass, dimensions and drag coefficient are known, air density at heights a little above perigee can be found from the rate of change of orbital period. This method is far more direct than the use of gauges which require preflight calibration in conditions not fully representative of the space environment.

The aerodynamic drag D acting on a satellite moving with velocity v relative to the Earth's centre is given by

$$D = \tfrac{1}{2}\rho v^2 F S C_D,$$

where ρ is the ambient air density, C_D the drag coefficient and S a reference area. The factor F, which allows for atmospheric rotation, is given by (Cook, King-Hele & Walker 1960)

$$F = \left(1 - \frac{r_p w}{v_p} \cos i\right)^2,$$

where r_p is the perigee radius, v_p the velocity at perigee, i the orbital inclination and w the angular velocity of the atmosphere.

The exact form of the equation that is used to determine air density from the rate of change of orbital period $\dot{T}$ depends on the eccentricity e of the orbit. For most satellites employed in density studies, however, the eccentricity lies in the range $0{\cdot}02 < e < 0{\cdot}2$ and the appropriate equation for the air density ρ_A at a height $\tfrac{1}{2}H^*$ above perigee is (King-Hele 1963)

$$\rho_A = -\frac{0{\cdot}157\,\dot{T}m}{FSC_D}\left(\frac{e}{aH^*}\right)^{\frac{1}{2}}\left[1 - 2e + \tfrac{5}{2}e^2 - \frac{H^*}{8ae}\left(1 - 10e + \frac{7H^*}{16ae}\right) + \frac{\epsilon}{e}\sin^2 i \cos 2\omega + 0\,(0{\cdot}01)\right], \tag{1}$$

where H^* is the best available estimate of the density scale height at perigee, ω is the argument of perigee, ϵ is the ellipticity of the atmosphere, a the semi-major axis and m the mass of the satellite. Although this result only applies for a density scale height gradient of 0·1, it can easily be modified for other values by slightly altering the numerical factor 0·157.

The accuracy of drag-determined densities can be assessed (King-Hele 1966) by considering equation (1). The effect of errors in the assumed density scale height is practically eliminated by evaluating the density at half a scale height above perigee. Provided H^* is not in error by more than 25 %, the error in the density will be less than 1 %. If attention is confined to spherical satellites, both the mass and the area should be accurately known. An uncertainty in the angular velocity of the atmosphere of 10 % introduces an error of about 1 % into F.

For most satellites the error in $\dot{T}$ can be kept to 1 % by a judicious choice of the time interval over which it is obtained, provided that the effect of solar radiation pressure is not large. The error in e will be negligible for an accurate orbit; even for the less accurate orbits used in density studies, the error in $e^{\frac{1}{2}}$ should not exceed 0·5 %. The error in a will normally be negligible, as will the errors contributed by the terms in square brackets in

(1). An error in perigee height will cause ρ_A to be evaluated at the wrong height and thereby produce an error in density of about 1% for an accurate orbit and about 7% for an orbit of 'average' accuracy (error of 0·0003 in e).

Another possible source of error is the model used in the derivation of equation (1). The equation is extremely insensitive to modifications of the model, however, and the error in ρ_A due to an inadequate model is unlikely to exceed 2% in a well-explored region of the atmosphere.

If the drag coefficient were accurately known, the total error in the density would not exceed 3% for an accurate orbit or $7\frac{1}{2}$% for an average orbit. Unfortunately, however, C_D is not accurately known and it is probably the largest source of error.

Satellites in orbit normally experience free-molecule flow and below 700 km the most probable molecular speed is small compared with the vehicle's speed, so that the random thermal motion of the atmospheric particles can be neglected, i.e. the flow is 'hyperthermal'. The drag coefficient therefore depends mainly on the degree of energy transfer between gas particles and the surface, i.e. on the energy accommodation coefficient.

At satellite speeds the incident molecules impinge on the surface with energies in the range 0·2 to 12 eV. So far very few experimental measurements of accommodation coefficients have been made in this energy range. Over the past few years, however, a number of theoretical studies have been made and these have indicated the important factors affecting the energy accommodation (Cook 1965*b*, 1966). Although, at present, there is perhaps not sufficient reason to abandon the value of 2·2 which has been widely used in recent years for C_D, it must be recognized that this value is subject to some uncertainty and may be too low, perhaps by as much as 15%, at the heights where gauge data is available. Results obtained by Moe (1966) are consistent with this statement: he obtained estimates for the accommodation coefficient, and hence C_D, by comparing the aerodynamic torque acting on the paddle-wheel satellite Explorer 6 (1959 δ1) with its aerodynamic drag.

2·2. *Pressure gauge–mass spectrometer techniques*

The majority of instrument measurements of density have been obtained from pressure gauges or mass spectrometers, which are normally used to measure conditions inside a chamber separated from the flow by an orifice. The gauge current is proportional to the number of particles, and hence the pressure, inside the chamber.

To relate ambient conditions, denoted by suffix o, to conditions inside the gauge, denoted by suffix i, the particles in both the atmosphere and the gauge are assumed to have Maxwellian velocity distributions. The pressure ratio across an orifice mounted on a vehicle in the free-molecule flow regime is then given by

$$\frac{P_i}{P_0} = \left(\frac{T_i}{T_0}\right)^{\frac{1}{2}} f(s), \tag{2}$$

where $f(s) = \mathrm{e}^{-s^2} + \pi^{\frac{1}{2}} s(1 + \operatorname{erf} s)$ and $s = (V\cos\alpha)/u_0$. In equation (2), P, T and u denote pressure, temperature and most probable molecular speed respectively, while V is the vehicle's velocity and α is the angle between V and the normal to the orifice. The particles in the gauge are often assumed to be fully accommodated to the temperature of the gauge walls.

Normally the pressure gauge is mounted on a spinning vehicle and the maximum and minimum pressures, $P_{\text{max.}}$ and $P_{\text{min.}}$, are measured over one spin cycle. For satellite-borne gauges the theoretical value of $P_{\text{min.}}$ is negligible and the gauge reading is due mainly to outgassing. If the minimum value of α is $\alpha_{\text{min.}}$, it can readily be shown by combining (2) with the ideal gas law that the ambient density is related to the maximum change in pressure over a spin cycle by (Spencer, Brace, Carignan, Taeusch & Niemann 1965)

$$\rho_0 = \frac{P_{\text{max.}} - P_{\text{min.}}}{\pi^{\frac{1}{2}} u_i V \cos \alpha_{\text{min.}}}.$$

Alternatively, the concentration of particles inside the gauge is related to the ambient concentration by

$$n_o = n_i \left(\frac{T_i}{T_0}\right)^{\frac{1}{2}} \frac{1}{f(s)}.$$

In terms of the difference between the maximum and minimum gauge readings, $n_{\text{max.}} - n_{\text{min.}}$, over a spin cycle, the ambient concentration is given by (Spencer, Taeusch & Carignan 1966)

$$n_0 = \frac{(n_{\text{max.}} - n_{\text{min.}}) u_i}{2\pi^{\frac{1}{2}} V \cos \alpha_{\text{min.}}}.$$

The accuracy of gauge measurements is limited by the accuracy and reliability of the absolute calibration, which depends on the range of pressure over which the gauge operates. Accurate measurements in a gas having a total pressure of order 10^{-6} torr or less are extremely difficult, while reliable calibration in an atomic oxygen environment is impossible at present. The values of density also depend on (i) the accuracy of the current measurement and telemetry system, (ii) knowledge of the gas composition, which determines u_i and also affects the pressure through the gauge sensitivity, (iii) the accuracy with which the orientation can be determined, and (iv) the accuracy of the trajectory data.

2·3. *Absorption of solar radiation*

The structure of the thermosphere can also be investigated by using continuous measurements of solar radiation. Since the cross-section for absorption of radiation in the region 44 to 60Å is almost independent of the nature of the absorbing particles, measurements of the intensity of solar X-radiation over this range can be used to evaluate the concentration of absorbing particles between successive observing positions (Landini, Russo & Tagliaferri 1965). This technique enables the total number density to be obtained as a function of height. The concentration of different species can be found from the selective absorption of specific emission lines in the extreme ultraviolet region. The main drawback of these techniques is the absence of reliable information on absorption cross-sections, which makes it difficult to estimate the probable accuracy of the results.

3. EXPLORER 17-GAUGE MEASUREMENTS

Explorer 17, which was designed and built by N.A.S.A., carried four pressure gauges, two neutral particle mass spectrometers and two electrostatic probes (Spencer 1965). This combination of instruments made possible the simultaneous measurement of absolute density and the concentrations of the neutral constituents.

3·1. *Pressure gauges*

Detailed results of density and temperature measurements made by Explorer 17 have been given by Newton, Horowitz & Priester (1965) for regions above six Minitrack stations. Values of density are obtained from the extremes in pressure measured over one roll cycle. Pressure was measured by four ionization gauges, two being of the Bayard-Alpert (hot filament) type and two of the Redhead (cold cathode) type.

The greatest errors arise from calibration errors. Uncertainty due to composition is reduced to less than 30% by using diurnally averaged data from the Explorer 17 mass spectrometer. Over much of the height range covered by the Explorer 17 data, atomic oxygen is the dominant constituent and it is necessary to consider the two limiting cases with total recombination and no recombination. By assuming conditions half way between, the experimenters claim that the maximum error from this source is 17% (see §§6 and 8, however). The errors (i) and (iii) mentioned in §2·2 are claimed to be less than 5% if attention is confined to passes for which the orientation is well defined. Errors due to satellite position should not exceed 1%, as with drag-derived densities. The absolute accuracy claimed by the experimenters varies between ±35% near 250 km and ±55% at 600 km. The errors are systematic and will, therefore, lead to discrepancies when the densities are compared with drag values. For heights below 500 km, the gauges appeared capable of repeatedly measuring the same density with a scatter of less than ±20%.

As with drag-determined densities, the gauge values show large variations which correlate with changes in the flux of solar radiation on a wavelength of 10·7 cm and the geomagnetic planetary amplitude A_p. There is also some evidence for density variations not associated with these indices. Newton *et al.* (1965) adjusted their data to magnetically quiet conditions ($A_p = 2$) and to a 10·7 cm flux of 83 W m^{-2} (c/s)$^{-1}$. Gauge measurements obtained below 300 km were then normalized to a height of 280 km on the basis of the model atmosphere of Harris & Priester (1962). The values were then plotted against local time and compared with results from drag studies normalized to the same conditions (see figure 1). The gauge densities are consistently lower, by a factor of over 2, than the values determined from drag studies. This discrepancy exceeds the expected error found by combining the uncertainties claimed by the protagonists of the two techniques.

3·2. *Neutral particle mass spectrometers*

The two neutral particle mass spectrometers aboard Explorer 17, which were of a double-focusing magnetic-deflexion type and employed an open ion source, measured the concentration of helium, atomic nitrogen, atomic oxygen, molecular nitrogen and molecular oxygen. The measurements are reported to have an accuracy of ±40% (Reber & Nicolet 1965). The total mass density can be obtained by summing the contributions of the individual constituents. Reber & Nicolet found that densities obtained in this way are generally higher than the values obtained from the pressure gauges by about 40% and lower by 30 to 50% than the values derived by Slowey (1964) from the orbit of Explorer 17.

An important finding from the mass spectrometer experiment is that there are large variations in the absolute concentrations of different species measured at the same altitudes and local times. For helium in particular the variations are much too large to be due to changes in exospheric temperature alone and must be attributed to changes in the boundary conditions at the height where diffusive equilibrium begins. This is in accord with the possible explanation (Cook 1967) put forward recently for the large semi-annual variation in exospheric density revealed by analysing the orbit of Echo 2 (Cook & Scott 1966).

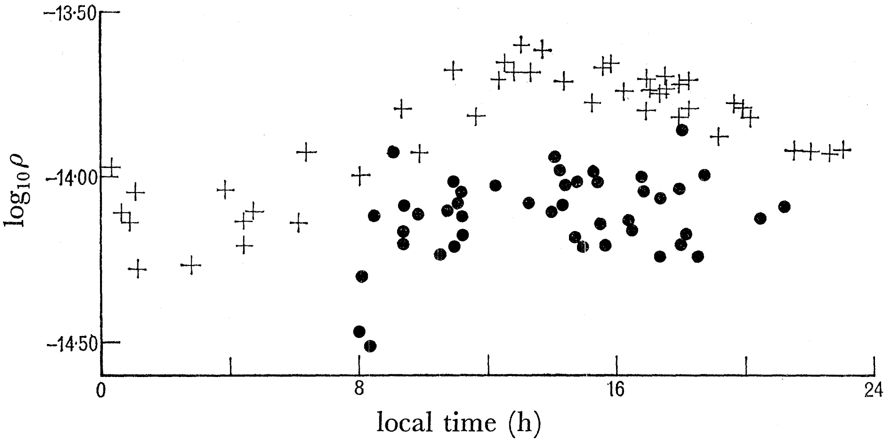

FIGURE 1. Comparison of air densities obtained from Explorer 17 gauges with drag values obtained from Injun 3 and Explorer 17. ●, Gauge data; +, drag data. (After Newton, Horowitz & Priester 1965.)

The daytime helium concentrations given in Fig. 14 of Reber & Nicolet (1965) are particularly interesting. If the differences in local times between the data points are borne in mind, there is a strong indication that near mid-day the helium concentration is higher in the southern hemisphere than in the northern. Since these measurements are for late May 1963, the helium concentration is high by day in the winter hemisphere. In the light of these results, it is not surprising that the orbits of Explorer 19 (1963–53A) and Explorer 24 (1964–76A) have revealed a diurnal bulge in the winter hemisphere at heights between 550 and 750 km (Keating & Prior 1967). For conditions of low solar activity, helium is a major constituent at heights near perigee for both of these satellites.

4. RUSSIAN PRESSURE GAUGE DATA

Values of air density obtained from gauges flown on two Russian vehicles are shown in figure 2. One set of values was obtained from the pressure gauge aboard Sputnik 3 and is for local times between 13 and 19 h on 16 May 1958 (Mikhnevich *et al.* 1959). The other set was obtained from an ionization gauge aboard a geophysical rocket launched at 4.30 h local time on 18 June 1963 (Mikhnevich 1966). Also shown in figure 2 are densities given by the Cospar International Reference Atmosphere 1965 for similar local times and the appropriate conditions of solar activity.

Both sets of gauge data show the same trend as the Explorer 17 results, although it is only in the region of 400 km that the drag values exceed the Sputnik 3 gauge values by a factor of as much as 2. The densities obtained from the rocket flight, which was under similar solar and geomagnetic conditions to those experienced by Explorer 17, differ from the model values by a factor which increases from 2 at 190 km to 2·6 at 350 km. There is now evidence that CIRA 1965 underestimates the magnitude of the day-to-night variation at heights below 250 km for conditions of low solar activity (King-Hele & Quinn 1965). For this reason values of night-time density from the latest orbital studies (King-Hele & Quinn 1966) are also shown in figure 2. These values, which were obtained from orbital decay during the years of low solar activity (1963–65), should apply for solar and geomagnetic conditions close to those prevailing at the time of the flight of the Russian geophysical rocket. The drag values of King-Hele & Quinn exceed the gauge measurements by a factor of only 1·6 at heights above 200 km.

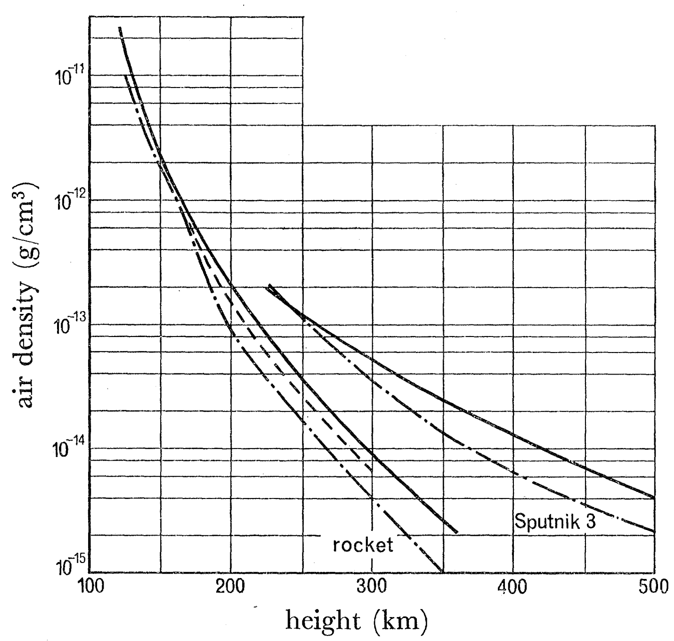

FIGURE 2. Comparison of air densities obtained from drag studies and pressure gauges aboard Russian vehicles. ——, CIRA 1965 for appropriate S and A_p; –·–·–, pressure gauge data; – – – –, minimum night-time density (1963–65) given by King-Hele & Quinn (1966).

5. THERMOSPHERE PROBE DATA

Since 1962 measurements of the concentration of molecular nitrogen in the thermosphere have been made using small omegatron mass spectrometers installed in 'thermosphere probes' (Spencer *et al.* 1965). These probes are removed from the contaminated region around the rocket by ejection at about 125 km. They then rotate end-over-end in a plane which is essentially fixed in space so that the gauge orifice faces forwards and backwards about once every 2 s. Molecular nitrogen is measured because preflight calibration is more reliable than with any other gas, while its distribution in the atmosphere is least affected by ionization and dissociation.

Results from early flights show a systematically lower concentration of molecular nitrogen than indicated by atmospheric models. The temperature of the atmosphere obtained from concentration profiles also tends to be lower than the model temperatures. This data, which is believed to have an accuracy of about 50%, is currently being re-examined.

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Recently an experiment has been performed to measure maximum daytime and minimum night-time concentrations under similar conditions using identical gauges calibrated together (Spencer *et al.* 1966). The experimenters have given a detailed discussion of the errors and claim an absolute accuracy of about 25 % and a relative accuracy of about 10 %. These errors are due entirely to uncertainties in calibration; contributions from the other sources discussed in §2·2 should be very small when molecular nitrogen alone is being measured.

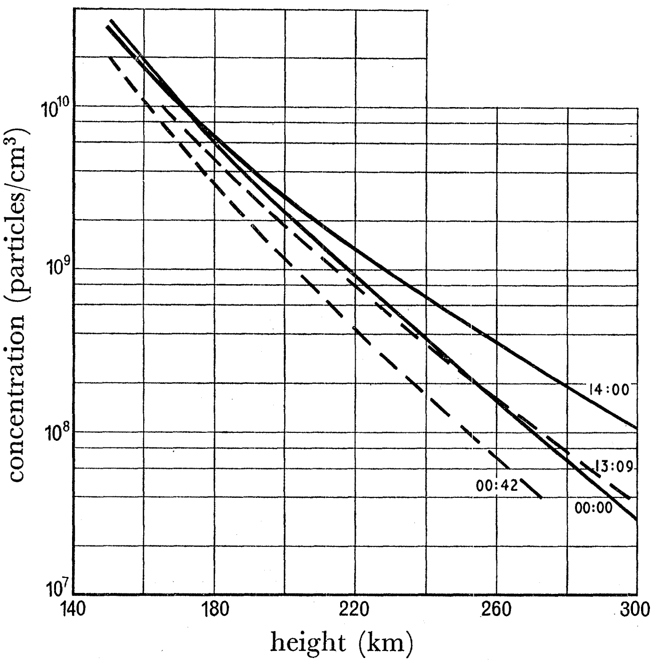

FIGURE 3. Comparison of mass spectrometer measurements of molecular nitrogen (Spencer *et al.* 1966) with values given by CIRA 1965. Numbers on curves indicate local time in hours and minutes. ——, CIRA 1965; – – –, mass spectrometer data.

The results of this recent experiment are illustrated in figure 3 together with the values given by model 2 of CIRA 1965. The flights took place over Wallops Island on 19 and 20 March 1965 when the prevailing solar and geomagnetic conditions corresponded to a minimum night-time temperature of about 740 °K. The most important point to note about the mass spectrometer data is that it shows an appreciable diurnal variation down to 170 km. This diurnal variation is not predicted by the model; it should be remembered, however, that when CIRA 1965 was constructed there were very few drag values of density at heights below 250 km for conditions of low solar activity. The pronounced diurnal variation down to 170 km is in accord with the results of the latest density determinations from satellite orbits. Maximum daytime and minimum night-time values of density found by King-Hele & Quinn (1966) for years of low solar activity, 1963–65, are compared in figure 4 with model 2 of CIRA 1965. The magnitude of the diurnal variation decreases from a factor of 2·1 at 250 km to about 1·4 at 170 km. The corresponding factors for the nitrogen concentrations are 2·2 and 1·3 respectively. Although the night-time flight did not quite give the minimum concentration, these values suggest that the relative error claimed by the experimenters is reasonable.

The molecular nitrogen concentration is systematically lower than the model data; the difference decreases from a factor of 2 in the region of 250 km to about 1·5 at 170 km.

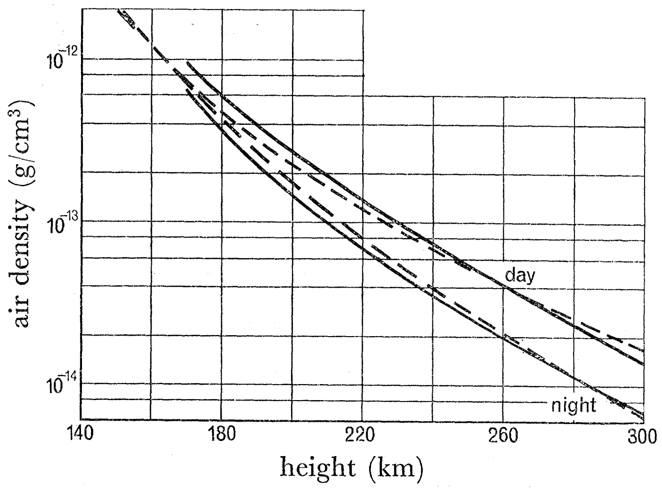

FIGURE 4. Comparison of maximum daytime and minimum night-time values of air density for the years 1963–65 with model 2 of CIRA 1965. ——, King-Hele & Quinn (1966); – – –, CIRA 1965 (model 2).

6. OTHER RECENT MASS SPECTROMETER DATA

Composition measurements in the thermosphere have been made using mass spectrometers on three recent rocket flights over White Sands, New Mexico. For the first flight on 6 June 1963 an open ion source was employed (Nier, Hoffman, Johnson & Holmes 1964) and values of air density were calculated for rocket positions where $s = 0$ on the assumption that the atmospheric particles (i) retain their ambient temperature, and (ii) are accommodated to the temperature of the ion source. On the bases of (i) the agreement with the drag data is reasonable at heights between 170 and 210 km, but on the basis of (ii) the gauge values are lower than the drag values by a factor which decreases from about 3 at 170 km to 1·5 at 210 km.

A rocket fired on 15 April 1965 carried three mass spectrometers, one of which employed an open ion source, while the other two were connected to a common chamber (Hedin & Nier 1966). The use of both open and enclosed ion sources on the same flight provides valuable redundancy which assists in the interpretation of the readings. Data from the enclosed instruments were analysed by means of the equations of §2·2 modified to take into account the transmission probability of the tube connecting the orifice to the chamber. The latter was calculated by Monte Carlo methods.

The use of a chamber reduces the uncertainty in T_i, which is probably responsible for the lower molecular nitrogen concentration given by the open ion source gauge. This result confirms that the atmospheric density obtained from the first flight on the basis of assumption (ii) is too low. When instruments are used to measure conditions inside a chamber there is always the possibility that a reactive gas such as atomic oxygen will be lost. Experimental confirmation of this was obtained from both the April 1965 flight and a later one on 15 July 1965, since the enclosed instruments observed neither atomic oxygen nor an enhancement of molecular oxygen, i.e. the atomic oxygen disappeared as a result of some unknown reaction (A. O. Nier 1966, private communication).

All concentration measurements obtained from the second and third flights are below the model values (Hedin & Nier 1966); rather surprisingly this is particularly true at heights below 170 km where the model is not based on drag data. In fact, the discrepancy tends to increase with decreasing height which is in the opposite direction to the trend shown by the thermosphere probe data.

7. Results of absorption measurements

The absorption of X-radiation in the range 44 to 60 Å has been measured by an instrument aboard the N.R.L. satellite 1965–16D and used to obtain values of total number density at heights between 120 and 200 km (Landini, Russo & Tagliaferri 1966). In general the number densities are about a half of the corresponding CIRA values, even at low heights. The accuracy of the data does not appear to be very good, however, and there is considerable scatter between values obtained at the same local times on different days having similar levels of solar activity.

Measurements of extreme ultraviolet radiation have been obtained from a rocket flight over White Sands at 10.04 local time on 10 July 1963 (Hall, Schweizer & Hinteregger 1965). Table 1 gives values of concentration and density obtained using absorption characteristics at nine wavelengths between 250 and 1300 Å. If the densities are compared with the drag values in figure 4, it is evident that there is good agreement at heights between 190 and 220 km; the absorption measurements lie midway between the extremes of the diurnal variation given by King-Hele & Quinn (1966). In view of the uncertainty in absorption cross-sections, the agreement is remarkable. It should be noted, however, that the actual absorption cross-sections used by Hall *et al.* (1965) were chosen to ensure that the scale heights of the various species were inversely proportional to their molecular weights. This is a reasonable approach provided that diffusive equilibrium prevails, as it almost certainly does above 170 km.

Table 1. E.u.v. absorption data given by Hall *et al.* (1965)

height (km)	concentration (10^9 particles/cm^3)			density (10^{-13} g/cm^3)
	N_2	O	O_2	
150	21	21	3·3	17·1
160	12	13	2·1	10·1
170	7·0	7·8	1·2	5·96
180	4·5	5·8	0·77	4·04
190	3·0	4·5	0·48	2·84
200	2·0	3·5	0·30	2·02
210	1·3	2·8	0·19	1·45
220	0·8	2·2	0·11	1·01

8. Discussion

The main conclusion to be drawn from a comparison of drag-derived densities with gauge-measured values is that the latter are systematically lower. This discrepancy, which was first highlighted by a preliminary analysis of the Explorer 17 pressure gauge data, is exhibited by all pressure gauge and mass spectrometer measurements.

Another important conclusion is that model atmospheres should not always be taken as representative of drag data. This statement applies particularly to conditions of low solar activity, for which the models are now known to be in need of revision both at heights below 250 km and also in the lower exosphere.

The difference between the values obtained from the two techniques tends to increase with height, i.e. to increase as the density becomes less and the reliability of the absolute calibration of the gauges decreases. The drag-derived densities should be just as accurate at 500 km as at 250 km. Although the Sputnik 3 pressure gauge data shows the same trend with height as exhibited by the thermosphere probe and Explorer 17 data, the drag values only exceed the gauge values by a factor of 2 in the region of 400 km. It is interesting to note that the daytime air density at 400 km in May 1958 is about the same as the density at 280 km in May 1963. This might be taken to imply the existence of a pressure-dependent discrepancy which could be attributable to gauge calibration.

At present no explanation can be given for the discrepancy between the drag values and the gauge measurements.The only real uncertainty in the drag method is C_D, and it must be admitted that the normally assumed value of 2·2 may be too low by 10 to 15% for a spherical satellite (Cook 1965*b*). The maximum possible error in the drag coefficient is 30%, and occurs for diffuse re-emission and zero accommodation (which is most unlikely); even this cannot possibly explain a difference by a factor of 2 or more.

Compared with the drag method, instrument techniques are extremely complicated and the uncertainty in absolute calibration could well be much larger than that claimed. The Explorer 17 gauges and the thermosphere probe mass spectrometers were all calibrated against the same absolute standard—a McLeod gauge. An important source of error in the normal use of this type of gauge has come into prominence since the launching of Explorer 17. A steady stream of mercury vapour flows from the gauge to the cold trap, which normally separates the gauge from the vacuum system under test. The mercury vapour drags gaseous molecules to be measured in the direction from the gauge to the trap and thereby reduces the pressure in the McLeod gauge by an amount which depends on the ambient temperature, the tube diameter, the gas pressure and the diffusion constant of the gas (Takaishi 1965). Errors as large as 25% have been reported for molecular nitrogen (Ishii & Nakayama 1962). This effect was not taken into account in the Explorer 17 gauge calibration and could well explain part of the discrepancy between the drag and gauge densities.

Laboratory calibrations are only performed in non-reactive gases. For other gases the relative ionization cross-sections are used to convert the measured gauge current to pressure or number density. Without direct calibration in the gas to be measured, however, the absolute number densities are liable to error. Hedin & Nier (1966) admit that only an estimate can be made of the possible error, and quote errors of 25 to 50% for their atomic oxygen number densities.

It was mentioned in §3·1 that, in order to relate the Explorer 17 pressure gauge readings to density, two limiting cases were considered for atomic oxygen. On the basis of the evidence mentioned in §6, it now appears that neither of the limiting cases will apply, since atomic oxygen simply disappears. This behaviour has been confirmed by recent thermosphere probe flights (N. W. Spencer 1966, private communication). An absorption pumping effect of this type could well explain why the pressure gauges read too low and almost certainly explains the 40% difference from the densities given by the Explorer 17 mass spectrometers. Difficulties in the interpretation of ionization gauge data have been listed recently by Friedman (1966). He suggests that the Explorer 17 pressure gauge data could be in error due to neglect of the transmission probability, since the sensors are located at the ends of tubes.

Although there is a discrepancy in the absolute values of density, both the drag method and instruments appear to provide good relative accuracy and can, therefore, give reliable information on density variations. In fact, recent results obtained by both methods have shown an appreciable diurnal variation at heights below 220 km for conditions of low solar activity. The present discrepancies in the absolute values should not be allowed to detract from the valuable information that can be obtained from both techniques.

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