4. MODELS OF THE EARTH'S UPPER ATMOSPHERE FROM SATELLITE DRAG

Jacques Vercheval

Institut d'Aéronomie Spatiale de Belgique
Av. Circulaire 3, B- 1180 Bruxelles

ABSTRACT

The first density data relative to the upper atmosphere were derived from the study of the orbital variations of artificial satellites due to the air drag. The analysis of these data revealed several types of variations associated in particular with the solar and geomagnetic activity. The same data were used as empirical support to the construction of the first atmospheric models; these models were produced assuming the diffusion equilibrium with a heating between 100 and 200 km and a heat vertical transport by conduction. The models were revised more particular when new density data relative to the mean thermosphere were available or when other atmospheric data were provided by other technics as mass spectrometry. By improving the formula used to calculate the density from orbital analysis, it has been possible to cancel the systematic discrepancies observed between the so obtained densities and those provided by "in situ" measurements.The physical and chemical structure of the terrestrial upper atmosphere is now relatively well known but there are still some imperfections in the existing models which justify that the study must be pursued.

INTRODUCTION

Before space exploration, nothing was known of the terrestrial upper atmosphere (understood here as the atmosphere above 150 km), except some scattered data obtained from "in situ" measurements with mass spectrometers or pressure gauges on board sounding rockets. The determination of the physical conditions in the upper atmosphere has really become possible with the launching of the first artificial satellites using the satellite itself as the measuring instrument. Indeed, the first and reliable method to determine the terrestrial atmospheric density at heights above 150 km was based on the analysis of satellite's orbital variations due to the air drag. The observed change in the orbit results from the integrated effect of the deceleration occuring at heigts near that of perigee where air density is the most important; atmospheric density at heights near the perigee can then be derived from satellite drag measurements. It is a simple and powerful method, which has yielded by far the greatest amount of information about upper atmosphere, mainly at heights between 200 and 1500 km. Different methods of deriving air density from satellite drag measurements have been developed by many authors: some of them have elaborated analytical methods [1], others have applied the methods of the numerical integration [2].
Many analyses were made relative to the density data inferred from orbital variations of satellites. Several types of density variations were rapidly recognized in the concerned atmospheric regions. Models of the upper atmosphere were constructed to make sense out of density data obtained at different heights, local times, locations on the Earth, and levels of solar and geomagnetic activity. The progress accomplished was the result of a gathering of different theoretical analyses, satellite drag data and other types

of measurements which were made year after year. Therefore, it is not easy to dissociate all the research work made in this field. For instance, the first very known Jacchia's model [3] referred to as J65, was patterned after those of Nicolet [4] of the IASB.

The models were regularly revised as more recent data were available, not only from the drag measurements but also from instrumented rockets and satellites. Jacchia published revised models known as J70, J71 and J77 models. The J77 model [5] was constructed with satellite drag data extending from 1958 to 1975 and taking into account the spectrometric measurements on the OGO 6 and ESRO 4 satellites concerning the relative concentrations of N_2 and O at 450 km. A new serie of models began in 1974 with the MSIS model, not based on drag data but well on mass spectrometer measurements and temperature data provided by incoherent scatter sounders. A first revision of this model referred as MSIS-77 was based on more and more temperature, density and composition data from many rocket flights, satellites and incoherent scatter radars[6-7]. A second revised model MSIS-86 was adopted as COSPAR International Reference Atmosphere CIRA 1986 [8].

AIR DRAG AND ITS EFFECT ON SATELLITE ORBITS

An uncontrolled satellite moving with velocity V relative to the ambient atmosphere is essentially subject to an aerodynamic force D acting in the direction opposite to V. This drag force is due to the continual collision of air molecules and atoms with the satellite. The orbit contracts with the perigee height decreasing very slightly. The drag force can be treated as a perturbing force. If D is the magnitude of the drag force per unit mass, it is customary in aerodynamics to write D in the form

$$D = \frac{1}{2}\frac{SC_D}{m}\rho V^2 \qquad (1)$$

where ρ is the density of the atmosphere, m is the mass of the satellite and S its cross-sectional area perpendicular to the direction of motion, and C_D is the drag coefficient.

The drag coefficient C_D depends on the mode of interaction between the satellite surface and the atmospheric molecules. It is necessary to know, for instance, how the atmospheric molecules are reflected or re-emitted by the satellite. Generally, the appropriate regime is that of free-molecule flow, that is to say without perturbation of the velocity distribution of the incident molecular flux by the re-emitted molecules. A value of 2.2 was recommended for use in the determinations of air density with an estimated error of about 5% to cover the majority of the satellites currently being analysed. The coefficient C_D has a value between 1 and 2 for large satellites in their last revolutions. There is no difficulty to evaluate the cross-sectional area of a spherical satellite, but if the satellite is of any other shape it may be far from obvious; however, for uncontrolled cylindrical satellites with a length/diameter ratio greater than about 2, a mean value can be given to S such that the resulting errors are never greater than 5 per cent.

Using the general theory of perturbations, it appears that the eccentricity **e** and the semi-major axis **a** are the only orbital elements which are subject to a significant secular variation with time. The semi-major axis **a** has the advantage to be linked to the orbital period **P** (the most accurately measured element) and moreover it is the only element which is not greatly affected by forces due to the irregularities of the Earth'gravitational field. Theories were therefore developed in order to derive numerical values of air density from the decay rate dP/dt and by using the following formula:

$$\frac{dP}{dt} = -\frac{3}{2}\frac{FSC_D}{m}a\rho_P\int_0^{2\pi}\frac{(1+e\cos E)^{\frac{3}{2}}}{(1-e\cos E)^{\frac{1}{2}}}\frac{\rho(E)}{\rho_P}dE \qquad (2)$$

where E is the eccentric anomaly measured from perigee along the orbit. The coefficient F is a factor which is introduced to take account of atmospheric rotation, i.e. to allow for the difference between the velocity relative to the Earth'centre and the velocity of satellite relative to the atmosphere. The relation

(2) clearly shows that the calculation of the density at the perigee ρ_p is only possible if one knows the distribution of the density along the orbit or a parameter Hρ called "density scale height" defined by the relation:

$1/\rho \; d\rho/dz = - 1/H\rho$ (3)

The first analytical theories have been developed in such a way that correct values of the density can still be obtained even when an incorrect density model is used; for a spherically symmetrical atmosphere with Hρ constant with altitude, this is true when "Hρ" is evaluated at half a scale height above perigee at a point which is close to the weighted mean of the heights over which the drag is effective ; the standard error is then less than 1% if the best estimate of Hρ differs from Hρ by up to 25%. Later, some more realistic atmospheric-density models were available to give a lot of density data relative to altitudes between 200 and 1500 km [9].

MAIN VARIATIONS OF THE ATMOSPHERIC DENSITY

The first density data derived from the drag of artificial satellites have revealed that atmospheric density decreases more slowly with height in the upper atmosphere than below 100 km, in the homosphere, where the composition is uniform (fig.1).

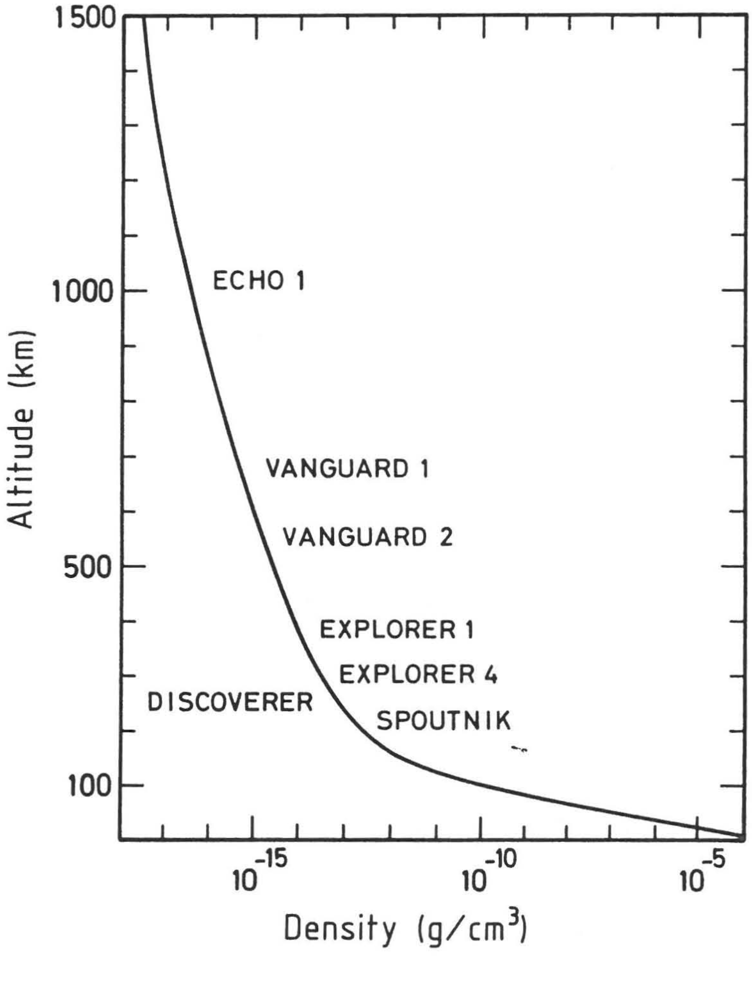

Figure 1: the orbital analysis has shown a slower decrease of the atmospheric density with height in the heterosphere.

Review of the densities collected during a few years makes it evident that the density of the upper atmosphere above 150 km is subject to considerable variations:

- a slow variation linked to the 11-year cycle of solar activity; at a height of 600 km, this effect can lead to a density variation up to a factor of 100 between a maximum and a minimum of the solar activity (fig.2); in the lower thermosphere, the effect is less important: a factor of 2 at 250 km.
- a variation with a period of 27 days corresponding to the rotation of the Sun; its amplitude is not so pronounced than that resulting from the solar activity (fig.3).
- short and fast fluctuations in connection with the geomagnetic activity, that is to say to the variations of the Earth magnetic field due to streams of charged particles, especially at times of solar flare outbursts (solar wind). This effect appears at any altitude, but its amplitude is the largest at 600 km where it can achieve a factor of 8 during a very strong geomagnetic perturbation (fig.3).
- a diurnal variation with a change of density between day and night by a factor up to 6 at a height which depends on the level of the solar activity; the maximum of the density occurs about 14 h, solar local time, and the minimum between 2 and 4 h in the morning.
- a semi-annual variation with the appearance,every year, of a deep minimum in July, a maximum in April and October and a secondary minimum in January; its mean relative amplitude is about 3 at 500 km; this variation has appeared as a rather complex phenomenon.
- seasonal-latitudinal variations as the so-called "winter helium bulge".

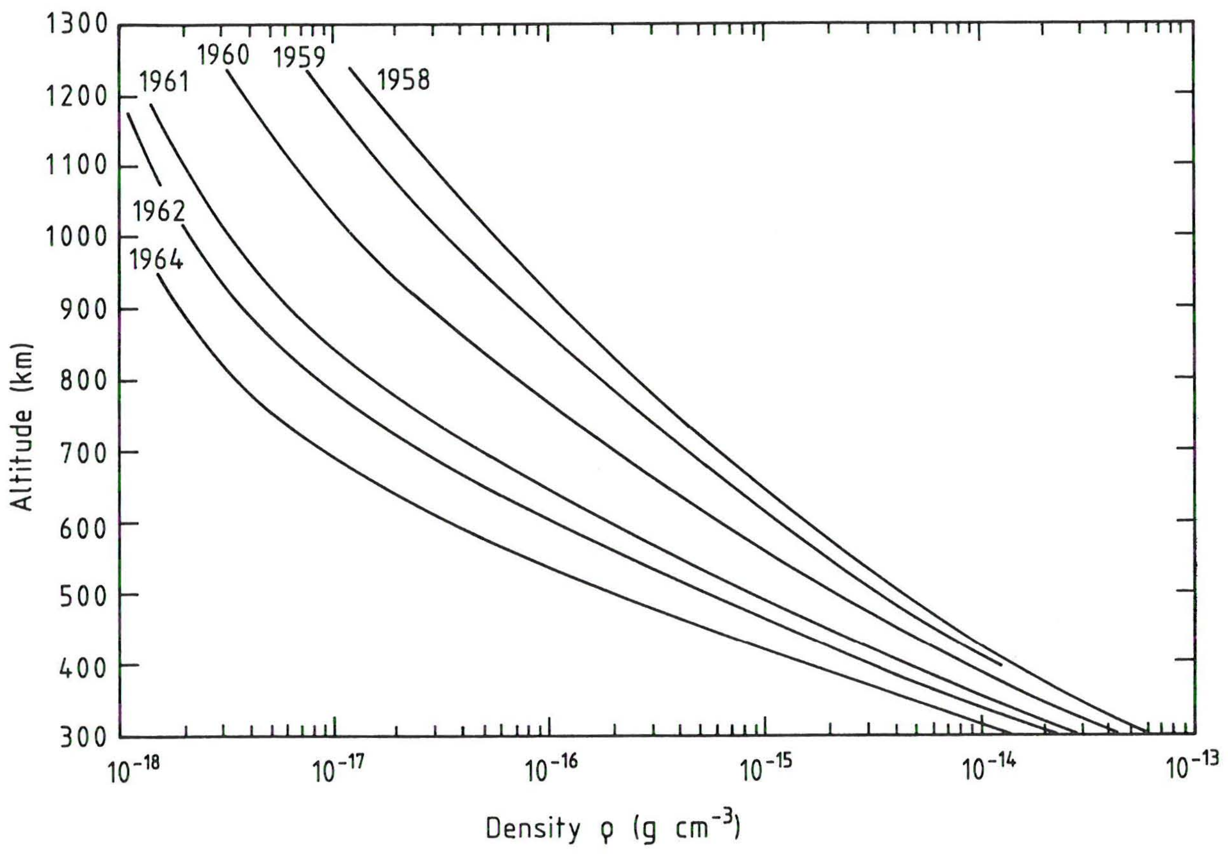

Figure 2: The mean density distribution strongly depends on the solar activity. The solar activity was very high in 1958 and minimum in 1964.

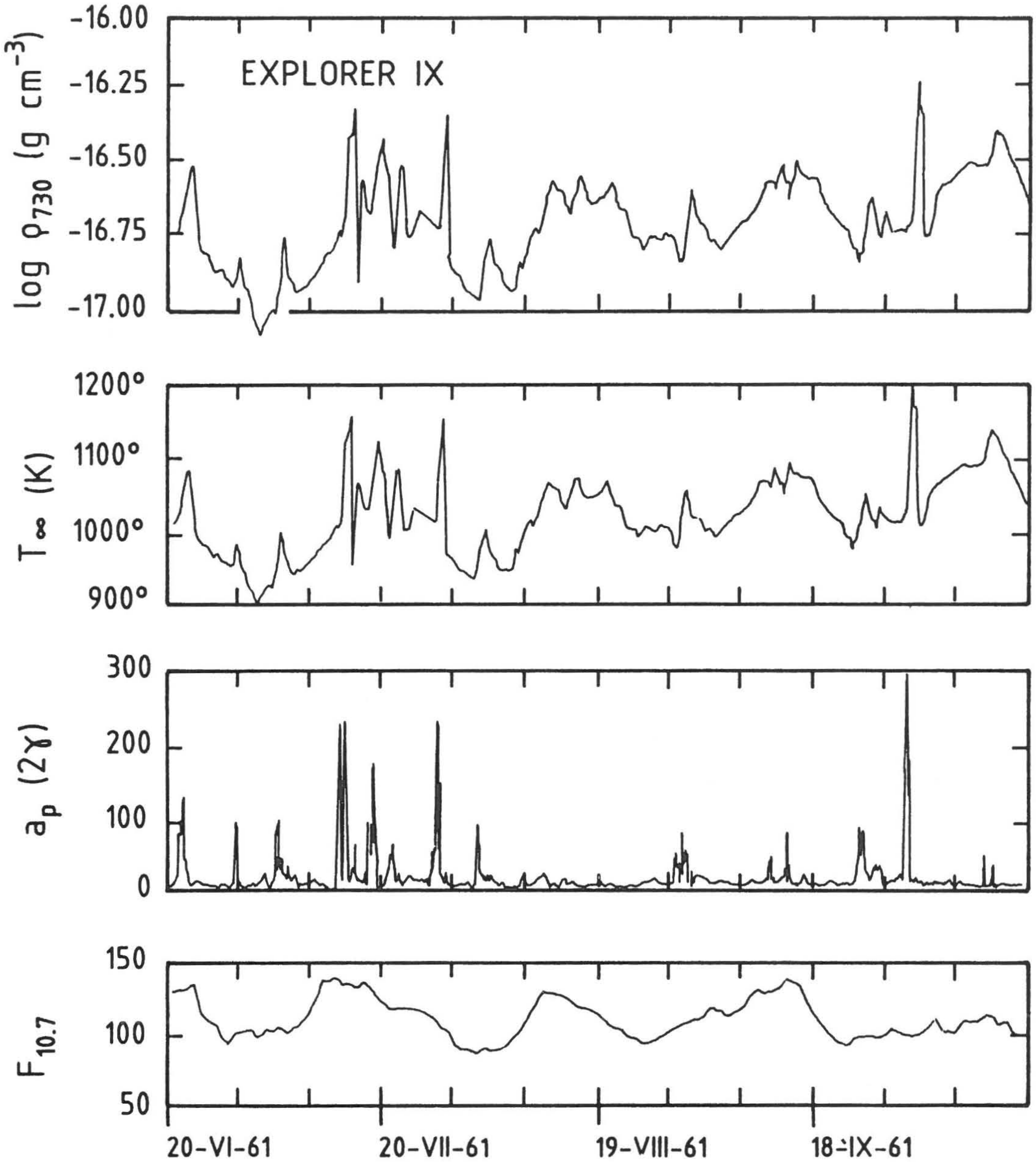

Figure 3: the atmospheric density at 750 km derived from the orbital drag of Explorer 9 satellite and compared with indices ap and F10.7 indicating the levels of the geomagnetic and solar activity.

THE FIRST ATMOSPHERIC MODELS

Observational results from satellite air drag, which mainly concern the vertical distribution of density at heights between 200 and 1500 km, are not sufficient to get a complete picture of the physical conditions in the heterosphere, the atmospheric region above nearly 100 km where the mean molecular mass cannot be taken as a constant parameter. The first coherent theoretical study to supplement observational results was due to Nicolet [4]: firstly, the slow decrease with height of the density in the heterosphere as revealed by the first satellite drag data can be explained by an increase of the temperature and a decrease of the mean molecular mass; the effect of the temperature prevails in the lower heterosphere called also "thermosphere" where the absorption of a part of the ultraviolet solar radiation by the oxygen molecules O_2 is responsible for the heating of this atmospheric region between 100 and 200 km. On the other hand, the decrease with height of the mean molecular mass is due to the gas diffusion in the field of gravity. Finally, a heat vertical transport by conduction is considered to explain the observed diurnal variation of the density. The first models were builded by Nicolet on the base of these considerations and proceeded from a fixed set of boundary conditions, temperature and partial densities, at 120 km. The use of these models to convert the densities data to temperatures led to a first picture of the temperature variation: the temperature progressively increases with height to reach at heights greater than 300 km (thermopause) asymptotic values between 300 °C and 1700 °C depending on diurnal and solar conditions.

It has been shown that Nicolet's 1961 model yielded consistent temperatures in the height interval between 350 and 800 km. The temperature is therefore a very convenient parameter to employ for a general analysis of atmospheric variations when satellites at different perigee heights are used. In the next following years, all atmospheric densities were converted to temperatures by interpolation of Nicolet's table (see example on fig.3).

Owing to the diffusion processes, the atmospheric composition at any given height changes with temperature; the upper atmosphere displays a structure of belts where molecular nitrogen (N_2), atomic oxygen (O_2), helium (He) and hydrogen (H) successively become the predominant constituents. The existence of a helium belt was first suggested by Nicolet [10] who showed that high densities derived from the rate of change of period of the Echo satellite orbit, that to say above 1000 km, could be explained by the presence of helium; Kockarts [11] has shown how helium becomes a major constituent at very high altitudes. A first detailed theory on the presence of helium and hydrogen in the upper atmosphere was also published by these two authors [12-13].

REVISIONS OF ATMOSPHERIC MODELS

Our density data analyses [14-17], performed in order to improve the first models which were mainly based on orbital data of satellites with perigee greater than 250 km, have shown that the main types of the density variations revealed at higher altitudes also exist in the mean thermosphere around 150 km that is to say in an atmospheric region which was for a long time one of the less inaccessible to the observation; in particular, the geomagnetic and semi-annual effects are very well pronounced; more generally, it has appeared that the models underestimated the amplitudes of all the variations in the mean thermosphere, probably because they were elaborated assuming constant boundary conditions at 120 km. However, in 1964, Nicolet [18] had already published a few models assuming a variation of ±10% of the temperature at 120 km. Using these models, we made an analysis [14-15] which led to suggest that a temperature variation at 120 km associated to a variation of the temperature at the thermopause could explain the vertical distribution of the amplitude of the semi-annual variation of the density up to 1000 km.

In 1970, following a critical survey of the density and composition data derived for a height of 150 km on the basis of all the available mass-spectrometer and EUV-absorption data, the density data were on an average 10 to 20% lower than those derived from the orbital analysis [19]. There was no explanation of these discrepancies between the two types of density data. At the same time, we noted [20] that the first known analytical theories relative to the determination of the upper atmosphere density from the orbital analysis presented a few limitations in the mean thermosphere: Kockarts [21] had shown that in this region the vertical gradient of the temperature as a result of the absorption of the ultraviolet solar radiation can take values which lead to gradients of the density scale height much more important that those assumed in the classical theories when an atmospheric density model must be choosen. Our new theoretical approach [20] was based on an hypothesis adequate for any physical conditions. The application of the new formula to orbital data of satellites with perigee lower than 200 km allowed to bring the drag measurements nearer to other experimental observations. Another analysis made by us [22] has showed that the semi-annual density variation in the upper atmosphere, at heights greater than 300 km, could be explained by combined changes in the exospheric temperature (at the thermopause) and in the composition at the lower boundary level at 150 km.

One of the last models based on satellite drag data was published by Barlier et al. [23]; Kockarts has contributed to the construction of this three-dimensional thermospheric model developed in terms of spherical harmonics by using 36000 satellite drag data which covered a time-period of almost two solar cycles. Such a model is able to represent the initial data file of 70000 values with an accuracy of the order of 10%. As an example, figure 4 shows the increase of the thermopause temperature, the total density and the concentrations n(He), n(O) and n(N_2) as a function of solar activity and for some other well defined conditions.

Comparisons between various semi-empirical thermospheric models have been made in detail by Barlier et al. [24] and Kockarts [25]; there are some discrepancies between the models and none of the semi-empirical models can represent perfectly all the geophysical aspects of the terrestial upper atmosphere. Therefore if we have now a good general picture of the upper atmosphere and its main variations, it is clear that its study must be pursued.

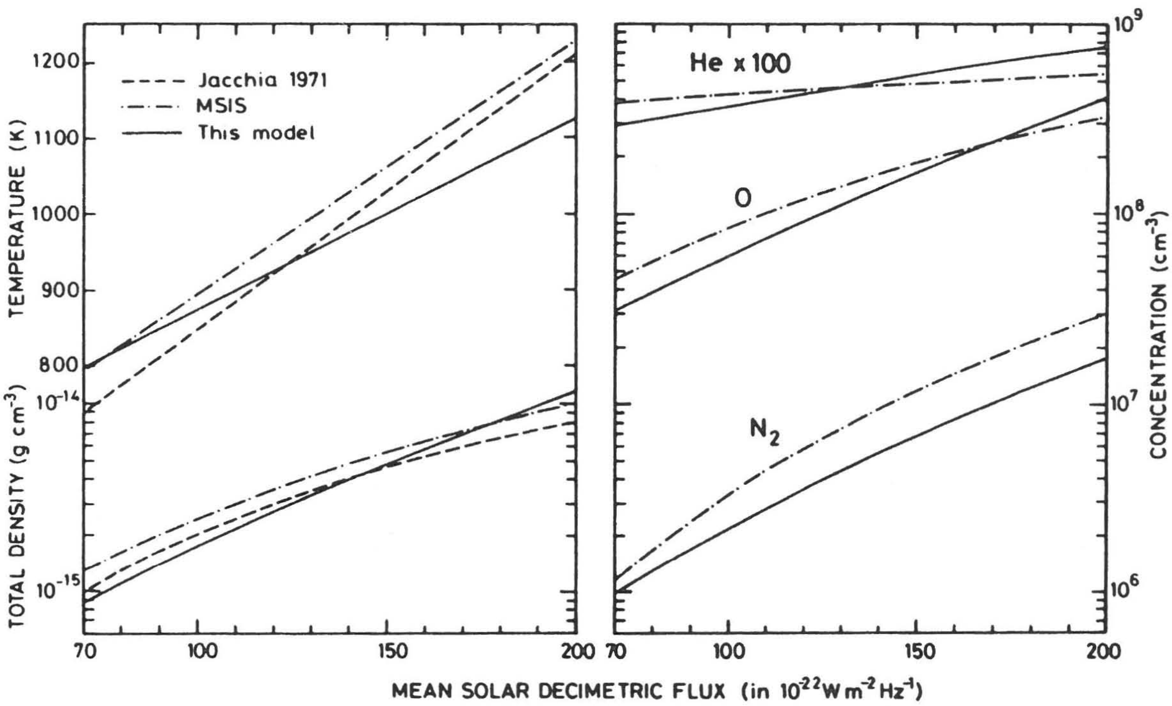

Figure 4: Models Barlier et al.: increase of the thermopause temperature, the total density and the concentrations n(He), n(O) and n(N_2) as a function of the average solar 10.7 cm flux F over three solar rotations centered on the September equinox, at an altitude of 400 km above the geographic equator and for a planetary index Kp=2. A comparison is made with J71 and MSIS models.

CONCLUSIONS

The Belgian Institute for Space Aeronomy (IASB-BIRA) has played a major role in the interpretation of the density data derived from the orbital analysis of artificial satellites and in the construction of the models of the terrestrial upper atmosphere; it proposed the first theory describing the physical and chemical structure of the upper atmosphere, suggesting for the first time the existence of a helium belt; its models were used during the first years coming after the launch of the first artificial satellite. The accumulation of density data led to a serie of revisions of the models. IASB-BIRA has also contributed to these revisions by analysing the different density variations mainly in the mean thermosphere, where "in situ" measurements were made as a complement to the drag data: the discrepancies between the two types of data were deleted by improving the known analytical theories relative to the determination of the atmosphere density from satellite air drag.
Actually, the physical processes in the upper atmosphere which make sense of observations made at different heights, local times, locations on the Earth ant levels of solar and geomagnetic activity, are not yet perfectly known. Density determination from satellite drag and in situ measurements by other techniques must be pursued at least during several solar cycles. However, in 1975, Jacchia [26] already wrote that "the variations in the uppermost parts of the terrestrial atmosphere can be much better accounted for than can the weather in the atmospheric region in which we live". Knowledge of the upper atmosphere is not only important in itself but has also a practical interest when it is a matter of estimating the orbital lifetime of an artificial satellite or predicting its epoch of re-entry; the most important part of inaccuracy comes then from the incertitude concerning the solar and geomagnetic activity!

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