Artificial satellites and the earth’s atmosphere

K Kasturirangan & P Padmanabhan
ISRO Satellite Centre, Airport Road, Vimanapura, Bangalore 560 017

The development and growth of space technology have helped man to explore the upper atmosphere in great detail and on a global scale through scores of artificial satellites and various precision instruments they carried onboard. Exploration of the atmosphere through satellites and utilization of the resultant knowledge for improving the theory of satellite orbits have gone hand-in-hand through a happy marriage of theory and practice. The harmonious interplay between the Earth’s satellites and the atmosphere is briefly brought out. Firstly, the effect of atmosphere on a satellite in orbit and its impact on satellite design and operation are described. Secondly, the understanding of the atmosphere achieved through satellite explorations is briefed. Recent and near future developments are also introduced.

1 Introduction

In the concluding paragraph of chapter 12 of his treatise “The Upper Atmosphere” Prof. S K Mitra remarked: “It can be confidently predicted that with improved types of rockets and with improved instrumentation and recording technique, many of the physical characteristics of the upper atmosphere, our knowledge about which is poor and which is gained only by indirect methods, will be directly measured and so yield sure and complete data”. At the time when these remarks were made, the highest altitude man had reached was 180 km using the rockets of the late 40s. The dynamic development and growth of space technology over the last 40 years have helped man to unveil and solve many mysteries of the upper atmosphere. The satellites that roared into the space in the 50s and later were not only carrying precision equipments to measure various parameters of the atmosphere, but were also proving themselves as accurate instruments for quantifying and modelling atmospheric parameters. The theory of satellite orbit dynamics in the presence of an atmosphere as well as the knowledge of the characteristics of the upper atmosphere were in their infant stages in the 50s and early 60s. Exploration of the atmosphere through satellites and utilization of the resultant knowledge for improving the theory of satellite orbits has gone hand-in-hand, through a happy marriage of theory and practice. This give-and-take relation between a satellite and its surrounding atmosphere has helped both these branches of science reach a level of maturity. Further they are proving themselves as effective tools in helping man preserve and protect his environment.

This paper tries to bring out, in a brief way, the harmonious interplay between the Earth’s satellites and the atmosphere. Firstly the effect of atmosphere on a satellite in orbit and its impact on satellite design and operation are described. Secondly the understanding of the atmosphere achieved through satellite explorations is briefed. Recent and near future developments are also introduced.

2 Effect of atmosphere on a satellite

The Earth’s atmosphere offers a resistive medium to a satellite, resulting in a drag force retarding its motion. Air drag is the second largest perturbative force acting on a near-earth satellite, the first being the gravity field perturbations arising from the shape of the Earth being an oblate spheroid. All applicable orbits are above 200 km of altitude. Up to about 2000 km the atmospheric effects are significant on a satellite above which gravitational attraction and luni-solar perturbations dominate. In the upper atmosphere the mean free path is large compared to the size of the satellites, so the drag force \( f_d \) can be derived from the free molecular flow model as

\[
f_d = \rho V^2 C_D A / 2 \tag{1}
\]

where \( V \) is the velocity of the satellite relative to the ambient atmosphere, \( A \) the cross-sectional area, \( \rho \) the density and \( C_D \) the drag coefficient. The important fact is that none of the parameters in this relation is known without error. The drag coefficient is calculated from the atom-surface interaction theories, the shape of the surface and the mode of particle flow. Many assumptions in its calculation need experimental proofs. A value between 2 and 2.2 is generally taken as \( C_D \) for altitudes between 200 km...
and 1000 km. At 2000 km, \( C_D \) can be about 5, below 200 km it is much below 2. When high precision estimate of the drag or its effect is needed, careful estimation of this parameter becomes necessary. Recent laboratory studies\(^1\) have shown that the value can be substantially below 2, pointing out that theoretical and experimental studies, including that in space, are needed to estimate drag coefficient accurately. Estimation of cross-sectional area \( A \) is generally simple if the orientation profile of the satellite in its orbit is known. But when the body is of irregular shape and tumbling, this parameter is difficult to estimate accurately. However, for all operational satellites the orientation (attitude) profile is normally known. Problem arises only for uncontrolled bodies. As regards density, accurate estimation and prediction of it has been one of the major activities in atmospheric science and it continues to occupy an important position.

### 2.1 Drag perturbations on orbit

Theoretically, the drag force affects all the elements of the satellite orbit. If corotation of the atmosphere with the Earth is neglected, the drag component tangential to the orbit can be seen to perturb semi-major axis \( a \), eccentricity \( e \), argument of perigee \( \omega \) and mean anomaly \( M \). The perturbations in argument of perigee and mean anomaly are periodic and negligible. The major effect is on \( a \) and \( e \) represented by

\[
\begin{align*}
\frac{da}{dt} &= -2bpa^2(1 + e \cos E)^{3/2}/(1 - e \cos E)^{1/2} \quad \ldots (2) \\
\frac{de}{dt} &= -2bpa(1 - e^2) \cos E(1 + e \cos E)^{1/2}/(1 - e \cos E)^{1/2} \quad \ldots (3)
\end{align*}
\]

where \( b = C_D A/2m \), \( E \) is eccentric anomaly and \( m \) is the satellite mass.

The conversion to time derivative is done with the relation

\[
\frac{d}{dt} = \frac{r/a}{\mu}(d/dt)
\]

where \( r \) is the radial distance from the Earth's centre and \( \mu \) is the Earth's gravitational constant. Here \( dt \) stands for time derivative.

Rotation of the atmosphere with the Earth introduces perturbations in \( a, e, \) inclination \( i \) and the right ascension of nodes \( \Omega \) (Ref. 3). The perturbations due to this on \( a \) and \( e \) are negligible as compared to those from the tangential component. When the perigee point of the orbit rotates, as generally the case is, the long term effect on \( \Omega \) becomes periodic and of small value when drag is not severe. These small perturbations are negligible except for fine accuracy orbit computations. The impact of atmospheric rotation on inclination is secular and its resultant change can be substantial over a long duration, considering the fact that inclination is an orbital element which tends to remain nearly constant. Lift force also introduces minor perturbations in \( \omega \) and \( e \) and is generally negligible in altitudes above 200 km or even 150 km.

When the satellite moves in an eccentric orbit, considerable portion of the drag effect occurs only over a limited arc of the orbit around the perigee, as the atmospheric density diminishes exponentially with height. This retarding force gradually decreases the apogee, keeping the perigee height nearly the same. Thus \( a \) and \( e \) decrease until the orbit is nearly circular. Further the orbit spirals into the denser layers of the atmosphere and gets burnt off. Once the height reaches below 150 km, the satellite can survive a few more revolutions only. Generally life time of a satellite orbit is assumed to end when the height decreases to 120 km. For orbits with \( 0.03 < e < 0.2 \), the life time \( L \) can be approximately calculated from observed values of orbital period \( T \) and its rate \( T \) using the relation (Ref. 3),

\[
L = eTF(e)/T
\]

where,

\[
F(e) = (3/4)[1 + 7e/6 + 5e^2/16 + (H/2ae)]
\times[(1 + 11e/12 + 3H/4ae + 3H^2/4a^2e^2 + O(e^3, H^4/2a^4e^4)] \quad \ldots (6)
\]

Here \( H \) is the density scale height. The function \( F(e) \) has a steep descent for \( e < 0.03 \) and hence may not produce satisfactory results for near circular orbits. For such orbits \( L \) can be calculated from the approximate relation

\[
L = -(3eT/4T)\left|I_0(z)/I_1(z)\right|K
\]

where

\[
K = 1 + 2eI_1(z)/I_0(z) + 9e^2/40 + O(0.008)
\]

\[
I_n(z) = (1/2 \pi) \int \exp(z \cos \theta) \cos n \theta d \theta
\]

and \( z = ae/H \). For fast calculations, \( I_0(z) \) and \( I_1(z) \) can be expressed in a series form of a few terms. These approximate analytical solutions are sufficient to predict the life time to fairly good accuracy, say 90%. Numerical integration methods incorporating detailed drag models and more accurate dynamical equations could also be used at the expense of computer time. However, accuracy of life-time prediction depends heavily on the atmospheric density and density scale height variations. Unpredictable solar activities and consequent perturbations in the upper atmosphere can offset any of
these predictions. Two examples which attracted public attention was the re-entry of Skylab-1 in July 1979 and the Solar Maximum Mission satellite in December 1989. Such uncertainties obscure the accuracy advantages of precision models. When long term prediction of life time is needed, such as for satellite design, orbit selection, mission planning and operation, etc., fast analytical methods in conjunction with parameters representing medium and extreme atmospheric conditions that are expected to prevail in the proposed duration of the satellite mission, are employed. Towards the end of the expected life-time, frequent orbit estimations, supported by extensive ground-based tracking are resorted to to estimate the decay rate accurately. The orbit decay profile of the Rohini Satellite-D2 (RSD2), which was put into a $393 \times 840$ km orbit on 17 Apr. 1983 by the Satellite Launch Vehicle-3 (SLV-3) are given in Figs 1-3. The satellite re-entered the atmosphere on 19 Apr. 1990 spending exactly 7 years in orbit. Predictions done with December 1989 orbit parameters showed the re-entry to occur between 10th and 25th of April. March 1990 observations predicted RSD2 to reach 150 km altitude on 21st April, which was revised to 19th April based on 3rd April orbit data (see Fig. 4 taken from Ref. 4). To know

![Decay of semi-major axis of RSD2 due to atmospheric drag. The satellite launched into a $393 \times 840$ km orbit by SLV-3 rocket on 17 Apr. 1983 re-entered the atmosphere on 19 Apr. 1990 due to natural decay. The figure gives the computed values of semi-major axis](image1.png)

**Fig. 1** - Decay of semi-major axis of RSD2 due to atmospheric drag. The satellite launched into a $393 \times 840$ km orbit by SLV-3 rocket on 17 Apr. 1983 re-entered the atmosphere on 19 Apr. 1990 due to natural decay. The figure gives the computed values of semi-major axis.

![Variation of eccentricity of RSD2 during its 7-year life in orbit. The graph represents the values determined from tracking data. No smoothing has been done on it. The decay behaviour is evident from the figure](image2.png)

**Fig. 2** - Variation of eccentricity of RSD2 during its 7-year life in orbit. The graph represents the values determined from tracking data. No smoothing has been done on it. The decay behaviour is evident from the figure.

![Uncertainty in life time prediction (the abscissa represents the number of days elapsed from March 18). The longer curve represents the decay profile of the semi-major axis predicted using March 18th orbit parameters. The prediction using April 3rd orbit data indicated the re-entry date as 19th April. The ground station got the last signals on 19th April (after Ganeshan et al.)](image4.png)

**Fig. 4** - Uncertainty in life time prediction (the abscissa represents the number of days elapsed from March 18). The longer curve represents the decay profile of the semi-major axis predicted using March 18th orbit parameters. The prediction using April 3rd orbit data indicated the re-entry date as 19th April. The ground station got the last signals on 19th April (after Ganeshan et al.)
the exact decay profile and re-entry time, extensive tracking and orbit computations were done from beginning of April till loss of signal on 19th April (Ref. 5).

2.2 Satellite re-entry
As the satellite re-enters the denser layers of the atmosphere below 100 km, the dynamics changes. With closer approach to the Earth, density increases rapidly and due to the drag, the velocity begins to decrease. Initially in the atmospheric phase, the deceleration increases; however, at some point the velocity begins to decrease more rapidly than the increase in density resulting in a maximum deceleration with subsequent decreasing deceleration. Associated with this deceleration pattern is the increased heat flux values. Also depending upon the conditions of re-entry, the spacecraft is likely to skip or be thrown out of the atmosphere by the centrifugal forces which overcome the Earth's gravitational attraction. Prediction of the trajectory below 120 km altitude needs complex modelling, and the accuracy is always marred by uncertainties in the density, drag coefficient and satellite relative velocity. Using a re-entry dynamics program, the possible impact zone of RSD2 was calculated. Figure 5 shows the footprint of the satellite from 100 km to impact point for a $C_D$ value of 0.5, assuming that the satellite did not get burnt-off. But such small satellites of the size, shape and mass of RSD2 usually get burnt-off at around 40 km altitude.

2.3 Impact of drag on satellite design and operation
The impact of drag on spacecraft design and operation is critical in certain classes of low earth orbits. The spacecrafts of the Stretched Rohini Satellite Series (SROSS), planned for operation in a circular orbit at 400 km altitude had to be given serious design attention to ensure at least 6-8 months of orbital life without extra fuel or reduction of exposed surfaces used for generation of solar power for operations. In the case of geo-synchronous communication satellites, drag has impact only in the transfer orbit phase. For example, when a spacecraft of the Indian National Satellite (INSAT) system passes twice through the perigee of transfer orbit in

Fig. 5 - Footprint of the trajectory RSD2 might have followed during its traversal below 100 km altitude. $C_D$ value assumed is 0.5. The satellite might have got burnt-off at about half way through this trajectory.
one day, the apogee height drops down by about 2.5 km. Care is taken that the satellite is kept in the transfer orbit for the minimal duration so that the apogee does not come down to an unfavourable height.

For high precision orbit estimation and control, air drag is a challenging factor. Precision orbit control is demanded by remote sensing and earth observation satellites. The orbits of such satellites are to be fine-tuned to predefined values of semi-major axis, eccentricity and inclination, so that the satellite always traverses over a well defined network of geographic routes (or paths) within narrow dispersion limits. To maintain the orbit fine-tuned, a good prediction of the drag is essential. This is hindered by uncertainties in the density predictions caused by unpredictable solar activities and imperfections in the density models. The high solar activity of 1989 had direct impact on the orbit control of the Indian Remote Sensing Satellite-1A (IRS-1A). Prediction of the orbit decay rate, required at cm/day scale, was not possible. This caused the footprint of the satellite (ground trace) to drift either slower or faster than planned, resulting in slight increase in the frequency of correction than planned. Figure 6 gives the profile of orbit maintenance corrections and ground trace shift. Corrections indicated at the upper portion of the graph were meant to make the drift of the ground trace follow a parabolic path with its vertex touching the abscissa. The early bends were the results of faster decay due to high solar activity. Similar behaviour has been reported for SPOT-1, the French remote sensing satellite during this high solar activity period.

It is natural to expect considerable increase in the atmospheric density during high-solar activity period. Figure 7 gives the density profile at 900 km altitude derived from the observed decay of the semi-major axis of IRS-1A. The top graph gives the 10.7 cm solar flux values. Correlation between the two is clear as one should expect. It is evident that finer modelling of the upper atmosphere is imperative for accurate prediction of the density variations and its impact on orbit decay to achieve precision control of low earth orbits.

2.4 Aerodynamic torque

Drag produces torques about the center of mass of a satellite. Below 400 km this is the dominant environmental disturbance torque. This torque has two components, one due to the displacement of the satellite's center of pressure (CP) from the center of mass (CM), the other a dissipation torque due to spacecraft spin. When the satellite is small and the spin rate is medium or low, the dissipation torque will be negligible compared to the displacement torque. For low earth orbits, the displacement torque is reduced by making CM and CP as close as possible by keeping symmetry about the axis parallel to the velocity vector. Predicted large values of aerodynamic torque had critical design effects on SROSS spacecrafts. The spacecraft has a shape of a cylinder with eight rectangular solar panels projecting out at 135° with respect to the axis, on one base of the cylinder. An initial on-orbit design configuration with the cylinder axis perpendicular to the orbit velocity had to be abandoned midway as it posed the problem of heavy torquing by the atmosphere, threatening attitude keeping. This forced an orbit configuration change with the cylinder axis parallel to velocity vector, at the expense of orbital lifetime. Aerodynamic torque is one of the critical parameters in the design and on-orbit maintenance of large space structures like the space stations. Large rigid as well as flexible appendages, moving robotic arms, possible add-on modules, crew movement, etc. can offset the CM-CP balance, giving rise to aerodynamic torques. In the structural and control design analysis of such space structures, accurate drag models are employed.

3 Exploring the earth's atmosphere

Satellites have proved as the only viable medium for understanding, explaining and quantifying the Earth's atmosphere on a global basis. Localized and short duration measurements with ground-based instruments, balloons and rockets have helped a long
way in the exploration of the atmosphere, but their limitations are clear for thermospheric, exospheric and magnetospheric measurements. The complex atmospheric variations—dynamical, physical and chemical—are governed or influenced by many factors emerging from the Sun's radiations, magnetospheric interactions and particle emission from the Earth's troposphere and stratosphere. Identification of these controlling factors, quantification of their contributions and prediction of what awaits next needs complex theoretical modelling supported by an extensive experimental data base covering the atmosphere on a global basis and over a large span of time. Satellites have played and continue to play the important role of providing such a data base. First they proved themselves as reliable instruments to provide indirect measurements of atmospheric density and then provided global platforms to generate the data base of experimental measurements. Such data obtained in recent years have thrown new light on the dynamics and composition of the upper atmosphere.

3.1 Estimation of density from satellite orbits

From the gas law and the hydrostatic equation, the pressure $P$ and density $\rho$ at a height $h$ above a reference height $h_0$ can be derived as:

$$P(h) = P_0 \exp \left( - \int_{h_0}^{h} \frac{(gW)}{(Rt)} dh \right)$$

$$\rho (h) = \rho_0 \left( \frac{W_t}{W_0} \right) \exp \left( - \int_{h_0}^{h} \frac{(gW)}{(Rt)} dh \right)$$

where $(Rt/gW)$ is the scale height, $P_0$ and $\rho_0$ are values at the reference height $h_0$, and $W$ and $t$ stand for molecular weight and temperature respectively. These relations are valid to several hundred kilometres. Here the vertical variations in temperature $t$ and molecular weight $W$ have to be taken into account. The actual values of $W$ and $t$ depend on many physical factors which exhibit high degree of dynamical variations. This implies that for the prediction of atmospheric behaviour and quantification of the effects of the controlling parameters, a model representing all observed and expected variations is needed.

The perturbative effect of the air drag on the orbit...
proved as a powerful tool to estimate the atmospheric density and temperature profiles. The drag force decreases the orbital energy of the satellite from which we can relate the rate of change of orbit period $T$ to the density $\rho$ as

$$\frac{dT}{dt} = -3r C_0 \rho A/m$$  \hspace{1cm} (9)$$

where $r$ is the radial distance from the Earth's center and $m$ is the mass of the satellite. Since most of the drag occurs at and around perigee, this equation can be used to estimate the drag at perigee altitudes with sufficient accuracy, using several observations of the orbital period. The densities thus obtained will be averaged values, in which time variations of less than an orbit period are averaged out. Intensive analysis of the orbit periods of the early satellites of the Sputnik, Vanguard, Explorer and Echo series, supplemented by measurements from satellite-borne mass spectrometers, pressure gauges and accelerometers provided a wealth of information on density and composition of the atmosphere. Temperature measurements using incoherent back scatter technique, Doppler broadening of the oxygen 6300Å line and other ground-based observations gave a knowledge of the temperature distribution in the atmosphere. These observations revealed many types of variations in the atmosphere which were classified as (Ref. 7): 27-day cycle variations, variations with 11-year solar cycle, variations with daily activity in the solar disc, diurnal and semi-diurnal variations, variations with geomagnetic activity, semi-annual variations, seasonal-latitudinal variations of the lower thermosphere and rapid density fluctuations. Strong dependence of the temperature variations on solar activity, atmospheric heating by solar EUV radiations and geomagnetic activity were evident in the data. Many of these variations, through their strong dependence on solar EUV and UV heating, yielded good physical interpretations. However, phenomena like the semi-annual variations, variations with geomagnetic activity, rapid density variations, phase delay between solar activity and temperature variations, etc. demanded more independent measurements to understand the physics behind them.

### 3.2 Atmospheric models

Observations on the orbital periods of satellites led to the development of improved models of the atmosphere extending up to 2000 km. The early models of CIRA 1965, CIRA 1972, Jacchia 65, 70 and 71 were based mainly on satellite drag estimates and tried to accommodate all observed variations by empirical relations for temperature, density and composition. In an improved model, Jacchia (J77; Ref. 8) included the changes in the composition of $N_2$ and $O$ observed by mass-spectrometers of the OGO-6 and ESRO 4 satellites. Figures 8-11 reproduced from Ref. 8 show the characteristic variation of the atmosphere derived on the basis of this model. Measurements of neutral density from mass spectrometers of five satellites (AE-B, OGO-6, San Marco 3, Aeros A and AE-C) and neutral temperatures inferred from ground-based incoherent scatter measurements were used to generate the MSIS 81 model (Ref. 9). A revised model of this, MSIS 83, accounts for the variations due to magnetic storms.
based on the three hour $A_p$ index and incorporates an 8 to 10 hour exponential decay in thermospheric density and temperature response after a heating event\(^\text{10}\).

These and similar models are widely used in atmospheric studies, satellite orbit computations as well as satellite mission analysis and design, with satisfactory results. Accuracies vary from model to model. However when it comes to estimation and prediction of satellite orbits to finer accuracies of a few metres or in predicting localized or short term variations in the atmosphere, difficulties generally arise. Comparison of the model values with measurements from satellite-borne accelerometers indicates lack of significant improvement in model accuracy during the past two decades\(^\text{11}\). This is probably due to the usage of second-hand data such as decimetric solar flux and planetary geomagnetic indices as input to the models. The atmospheric variations should have been ideally modelled using solar XUV radiation and ionospheric current data, but difficulty in their measurements lead to the usage of the above indices to represent them. A correlation study of seven atmospheric models (Jacchia 71S, 77S, 77D, DTM 1978S, 1978D, MSIS 1983S, 1983D) suggests that the response of the atmospheric models to changes in the 10.7 cm flux needs examination\(^\text{12}\). Modelling the response of the at-
mosphere to geomagnetic fluctuations with the use of the magnetic index $A_p$ is not all that satisfactory. The study also suggests, based on the analysis of the precipitating energy influx measured by NOAA/TIROS weather satellites, that inclusion of the precipitation index can improve the models. The precipitation index quantifies the intensity and spatial extent of the precipitating energy influx and is an indicator of magnetospheric activity. These observations indicate that improved atmospheric models, based on theoretical investigations, better indicators of the solar-magnetic activities and dynamical models, are to be developed to represent the atmospheric variability with higher fidelity.
3.3 Recent observations

Many of the variations observed in the upper atmosphere found explanations from the solar EUV heating. But the knowledge of the physics behind the observed structure and the variations in the thermospheric parameters were not perfected. Scientific discussions on understanding the physics of the atmosphere led to the conclusion that a full appreciation of the near-space environment would require comprehensive experimental and theoretical studies of the physical, chemical, dynamical and radiative processes that couple the Earth's magnetosphere, ionosphere and upper atmosphere. Many satellites were flown with precision equipments to make independent in situ measurements of the atmospheric parameters. The data from the Atmospheric Explorer satellites, NOAA/TRIOS satellites, International Sun-Earth Explorers (ISEEs), and Dynamic Explorer satellites have made significant contributions in explaining the atmosphere.

The atmospheric explorer satellites conducted measurements to study the changes in the ozone field, Earth's heat balance and energy conservation mechanism. The ISEE satellites made measurements of the interplanetary magnetic field (IMF) and could detect solar activities early which could tell whether any atmospheric phenomena were caused by magnetosphere or by the Sun. The data collected were successfully used in exploring IMF dependency of high latitude thermospheric winds. The space environment monitor on the TRIOS/NOAA meteorological satellites has been measuring the energy influx of precipitating charged particles over the polar region since 1978. The data collected have been used to define a precipitation index which is an estimate of the energy deposited into a single hemisphere's atmosphere by auroral particles\(^\text{13}\). The impact of such energy in the atmospheric density model has been noticed as significant\(^\text{12}\). The data provided by the Dynamic Explorer satellites have helped to make considerable improvement in the understanding of the momentum and energy coupling between magnetosphere, ionosphere and upper atmosphere\(^\text{14}\). The various instruments on these satellites measure (i) in-orbit-plane component of the neutral wind vector and the thermospheric kinematic temperature as a function of altitude, (ii) neutral wind and kinetic temperature, (iii) auroral luminosity distribution, and (iv) neutral atmospheric composition.

Observational data from these satellites complemented by classical theory have led to important conclusions. The high latitude thermospheric wind pattern has shown definite dependencies on universal time, local time, season, IMF orientation and geomagnetic activity, and these dependencies could be quantified to certain extent. The identification and quantification of the dependency of neutral wind circulation pattern on IMF orientation illustrates the strong coupling that occurs from solar wind through magnetosphere and ionosphere into neutral atmosphere. It may be that the thermospheric composition and density structures at high latitudes are also strongly related to IMF orientation. The variations of ion-neutral momentum transfer time constants show large dynamic range of the coupling between magnetosphere and thermosphere and vary within a solar cycle. Comparison of results from the analysis of experimental measurements with the results of simulation using theoretical thermospheric general circulation models (TGCM) shows considerable agreement on the mean day-to-night circulation caused by EUV and UV heating augmented by magnetospheric process and ion-neutral momentum transfer. Seasonal variations in temperature and composition, though a strong function of solar heating, have significant magnetospheric forcing. The striking agreement between theoretical results and experimental data is an indication that a better, if not full, understanding of the physics of the atmosphere is round the corner.

In close analogy to the explorations of the atmosphere above 100 km, the close-Earth atmosphere has been a subject of interest, scientific curiosity, exploration and (recently) concern. Measurements from the NOAA, NIMBUS and Earth Radiation Budget (ERB) satellites have given valuable information on this portion of the atmosphere. Two most important observations of great concern are the possible rise in the overall average temperature of the globe by 1° to 2° (as of now, still debatable) and the famous spring-time ozone hole over the Antarctica. Whether the observations we have today are indicators of certain long term trends of the planet as a whole or are some chemical or meteorological phenomenon specific to some areas, is a matter of considerable significance. To answer such questions and develop predictive capabilities, complete understanding of this portion of the atmosphere is essential. This calls for extensive modelling of the chemical and dynamical processes that happen here. This will need extensive global data base on the measurements of the concentration of key sources of particles migrating from troposphere to stratosphere and above, their sinks, reactive intermediaries, direct wind measurements, solar UV input energy and so on. Efforts are on to collect such data from satellites. The Upper Atmosphere Research Satellite (UARS) of NASA is one meant for such measurements\(^\text{15}\). Two instruments, the so-
lar ultraviolet spectral irradiance monitor and the solar-stellar irradiance comparison experiment, will monitor the spectral distribution and intensity of the solar UV radiance. A particle environment monitor will determine the magnetospheric energy input from protons and electrons. A fourth instrument, the active cavity radiometer irradiance monitor will measure irradiance of the solar disk at all wavelengths. The data provided by these satellites and future ones that will follow may give a clear picture of what is taking place in the upper atmosphere and tell what man can do to avoid destruction of the delicate environmental balancing system.

Such explorations become important when we understand the fact that human impacts on the Earth have already reached a scale that, in many cases, approximates that of the natural process. Thus today humanity is facing an unprecedented challenge of collective actions to bring about ecological sustainable development. Earth satellites can definitely help as monitoring and warning instruments in our endeavour to sustain a habitable Earth.

4 Conclusion

The pioneering investigations of Prof. Mitra of upper atmosphere have acquired a new significance in the space era. The optimistic prediction Prof. Mitra made forty years ago has become a reality with satellites routinely exploring the atmosphere as a part of the man’s endeavour to understand the Earth’s environment.

References