Rocket- and satellite-borne optical instrumentation for aeronomy and atmospheric sciences studies

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The significant role of rocket- and satellite-borne optical instrumentation in aeronomy and atmospheric science research is reviewed. Beginning with the pioneering rocket measurements in the fifties and the sixties of the solar UV and EUV spectrum using rocket monochromators, optical instrumentation has played an increasing role in the study of solar spectrum, atmospheric structure, dynamics, composition and energetics. The major development of the last two decades—middle atmospheric science as a distinct discipline—owes a great deal to satellite-borne optical instrumentation. Developments in sensors, data analysis techniques, image processing and computation techniques together with development of suitable platforms have played a key role. In recent years several sophisticated optical techniques have been developed in India and are in operating use for ground-based research in aeronomy and atmospheric sciences. These have potential for application from space platforms.

1 Introduction

Optical techniques were the major tools for space science studies even well before the advent of rockets and satellites. However, the advent of rockets and satellites significantly enhanced the scope of these techniques in space science research. It became possible to go above the absorbing regions of the atmosphere and explore space at UV and IR wavelengths. These wavelength bands play fundamental roles in atmospheric radiation balance, energetics and dynamics. Hence they are of great significance not only for aeronomy and atmospheric science studies, but also for solar physics and planetary atmospheric studies. Further, space platforms have opened up new research disciplines, e.g. satellite remote sensing, in which optical techniques have played the major role. Many of the developments in satellite remote sensing have been exploited for space sciences, especially in middle atmospheric research. Optical techniques have continued to provide through the past 3-4 decades substantial (almost half of all) new information relevant for aeronomy and atmospheric science research. In recent years there have been exciting developments in optical instrumentation because of new detectors, advances in computer technology and image processing techniques. Most of these have been of an interdisciplinary nature involving astronomy, aeronomy and atmospheric sciences, meteorology and remote sensing. The following sections give a brief outline of the major developments in optical instrumentation on rockets and satellites for aeronomy and atmospheric science research. Also follows a brief account of the developments on the Indian scene.

2 Solar flux measurements: UV and EUV part of the spectrum

Until the advent of rockets and satellites, the solar spectrum was studied mostly in the ground reaching visible region. Photographs of the solar spectrum taken from mountain tops and balloons had revealed the extension of the spectrum beyond the ground level cut off at 2900 Å. Consequently when the German V2 rockets became available for scientific research in the post-war period, one of the first rocket experiments conducted was to study the ultraviolet spectrum of the sun. A systematic programme of solar spectroscopy in the ultraviolet and extreme ultraviolet was launched in the fifties and the sixties with the Naval Research Laboratory (NRL) and the Air Force Cambridge Research Laboratories (AFCRL) of the USA playing leading roles in it.

The first rocket measurement of the solar spectrum was made by Baum et al. of NRL, USA on a V2 rocket in 1946. The spectrograph used a concave grating of dispersion 40 Å/mm in the first order. Conventional slits were replaced by 2 mm dia LiF spheres which formed the image of the sun behind beads and served as source points for the spectrograph. The field of view was large (140° cone) to accommodate for varying angle of incidence due to vehicle roll and spin. There was no pointing control
system. The attempt may appear crude from present day standards, but it was indeed a pioneering experiment and extended the solar spectrum down to 2100Å.

Baum et al.'s pioneering attempt was followed by several experiments during the fifties. For wavelengths lower than 2100Å, due to the low intensities it was necessary to hold the image of the sun on the spectrograph slit and increase the exposure factor, sun pointing systems were essential. At first single axis sun followers were used to compensate for rocket spin. Stacey et al.² provided the first biaxial control system which could overcome both roll and yaw effects. A photoelectric angular error sensing system provided a servo mechanism with an accuracy of 1 min of arc and 5-10 sec resolution.

The first VUV spectrograph was flown on an Aerobie Hi rocket on March 13, 1959. Johnson et al.³ used a normal incidence spectrograph which provided solar UV spectra down to 500Å. In these early experiments the spectra were obtained on photographic plates which were later read by a photoelectric densitometer. The first telemetry monochromator which dispensed with the need for instrument recovery was flown by Hinteregger and coworkers of AFCRL in 1960 (Ref. 4). This provided another quantum jump in measurement capability.

The first complete spectrum of the solar EUV radiation from 2100Å down to 170Å was obtained when an Aerobie Hi rocket was flown on August 22, 1962 (Ref. 5), carrying a composite of four spectrographs. Two normal incidence spectrographs, one with a grating of 1200 lines/mm and a resolving power of 0.2Å covered the wavelength range 2000-1200Å and the second a higher resolution instrument with a resolving power of 0.07Å covered the wavelength range 1250-800Å. For lower wavelengths, two grazing incidence spectrographs with a resolving power of 0.05Å were flown. The spectrograms showed that the nature of the solar spectrum rapidly changes from 2100Å to 1200Å from a continuum with an equivalent temperature of 5500 K at the longer wavelengths and characterized by a number of Fraunhofer lines indicating that the radiation is of photospheric origin, to a transition region in the 2000-1950Å range where the Fraunhofer lines become faint and the emission lines begin to appear indicating that the radiation comes from the region between the photosphere and the chromosphere. Finally at λ<1500Å, the continuum changes its character completely. Large number of emission lines appear and there is an almost complete absence of Fraunhofer lines indicating that the radiation is of chromospheric origin. Based on the early rocket measurements, Friedman⁶ gave the first quantitative data on relative intensities of the solar EUV spectrum down to 900Å. Several new and exciting features of the solar spectrum in this wavelength region were revealed by these and later measurements⁷. These include large number of chromospheric emission features at λ≤500Å including the helium emission at λ = 584Å and 304Å. High resolution measurements of the line profiles of the hydrogen Lyman-α and Lyman-β lines clearly showed the self reversal and the absorption core due to telluric hydrogen (Fig. 1). These were epoch making events in space science research using optical instrumentation on sounding rockets. They were important not just from the technology point of view, but also from the science point of view as they initiated new directions in space science research, aeronomy and solar physics.

2.1 Solar flux variations

The Orbiting Solar Observatory, OSO-1, launched in March 1962 provided the first opportunity to study the temporal variations of solar EUV flux. It provided a stable platform for a grazing incidence scanning (Hinteregger type) monochromator which monitored solar EUV flux in the 50-400Å wavelength range. Both quiescent and disturbed time measurements were made. First set of results on the solar rotation as well as solar activity related variations was obtained. It was found that the variation was extremely sensitive to the wavelength range⁸. Coronal emission features, He 304Å line and the Fe 284 and 335Å lines, were monitored. Comparative study of their variations with 2800 MHz flux and other indicators of solar activity identified for the first time the association of solar EUV with localized features/active regions on the solar disc and gave evidence of centres of activity on the sun. These observations initiated theoretical models of coronal electron density and temperature. In the subsequent years the solar EUV spectrum has been systematically monitored⁷,⁸ by mounting scanning monochromators onboard the Atmospheric Explorer series of satellites. These and the rocket experiments in the eighties⁹,¹⁰ were highly coordinated programmes with great care for standardization and calibration of the instruments. Satellite measurements were frequently calibrated by rocket measurements using the same type of instrumentation. Emphasis was on reliable and absolute measurements. We now have a standard solar spectrum for EUV¹¹, reliable information on the variability of solar UV and EUV fluxes not only for the 11-year cycle but also for the 27-day rotation¹². The most recent development in the field is
in the measurement of total solar flux from satellites using the so called active cavity radiometer (ACRIM). Even though solar constant measurements have a long history, the Nimbus 7 Earth Radiation Budget Experiment and the SMM ACRIM experiment prescribed the value of solar constant with an accuracy better than ±0.5% (Ref. 13). The efforts of the past decade have quantified the short-term and the long-term variations of the total solar flux. There is a small but significant variation of the total solar flux on the 11-year and 27-day time scales and much of this is contributed by changes in the EUV part of the spectrum.

3 Atmospheric structure and composition

Optical techniques have also been used to study the structure and composition, trace gas abundances as well as dynamical features in the atmosphere. One of the earliest and still widely used techniques is absorption spectroscopy using sun as the light source. Most of the atmospheric constituents including trace gases have well defined absorption features in different parts of the solar electromagnetic spectrum. This can be used to determine the abundances of these constituents provided the absorption cross sections are known. The type of instrument used depends on the wavelength region and the resolution required. Some sort of pointing control is generally required.

One of the first set of measurements of thermospheric composition was made using the absorption technique. Using a scanning monochromator on a rocket, Hinteregger showed that by measuring the attenuation profile of solar EUV radiation at three or more wavelengths, it is possible to estimate the concentration of the three major species, namely, N₂, O₂ and O in the thermosphere. This measurement provided one of the first verifications of diffusive equilibrium in the thermosphere.

3.1 Ion chambers

Absorption spectroscopy has been extensively employed to study the structure of the mesosphere and to some extent lower thermosphere as well. The wavelength used is in the 1050-1500 Å region and the main absorber is the major constituent molecular oxygen. This radiation is mostly absorbed in the 90-150 km altitude region of the atmosphere. The instrument used is an ionization chamber. A cylindrical chamber, generally made of oxygen-free copper (sometimes ceramic, gold plated inside), is filled with a suitable gas and sealed with a suitable window in the front. The window allows only radiation with wavelength larger than the cutoff wavelength to enter the chamber. The radiation entering the chamber can ionize the gas within the chamber if its photon energy is greater than the...
Fig. 2(a)—Mesospheric temperatures obtained from the Lyman-α ion chamber measurements at Thumba (After Subbaraya & Shyam Lal17).

(b)—Mean daytime mesospheric temperatures obtained from Fig. 2(a) compared with CIRA model values as well as the evening time M-100 rocket measurements (After Subbaraya & Shyam Lal17).
Table 1—Some ionization chambers in common use for ultra-violet radiation measurements

<table>
<thead>
<tr>
<th>Window material</th>
<th>Filling gas</th>
<th>Spectral response, Å</th>
</tr>
</thead>
<tbody>
<tr>
<td>LiF</td>
<td>Carbon disulphide</td>
<td>1050-1240</td>
</tr>
<tr>
<td>LiF</td>
<td>Nitric oxide</td>
<td>1050-1340</td>
</tr>
<tr>
<td>CaF₂</td>
<td>Nitric oxide</td>
<td>1230-1340</td>
</tr>
<tr>
<td>CaF₂</td>
<td>Acetone</td>
<td>1230-1290</td>
</tr>
<tr>
<td>BaF₂</td>
<td>Ethyl sulphide</td>
<td>1350-1480</td>
</tr>
<tr>
<td>Sapphire</td>
<td>Mesitylene</td>
<td>1420-1480</td>
</tr>
<tr>
<td>Sapphire</td>
<td>Dimethylhydrazine (1,1)</td>
<td>1420-1590</td>
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ionizing potential of the gas. The resulting current is collected by the collecting electrode which is suitably biased and measured by using appropriate electronics. For a given window material and filling gas the chamber becomes a narrow band detector. Table 1 shows some commonly used combinations. Of special significance is the nitric oxide filled chamber with LiF (MgF) window which has a pass band of 1050-1240 Å (1150-1240 Å) since most of the (> 90%) solar radiation in this wavelength band is constituted by the hydrogen Lyman-α (1216 Å) line and it can be considered as a Lyman-α detector. It can be used to determine O₂ density and neutral temperature in the 60-90 km region and hence is ideally suited for mesospheric studies. Due to the large intensity of the radiation the ion chamber can be operated in the unity gain mode, while for the other wavelength bands a larger bias voltage on the anode is used to make the ion chamber operate in the gas gain mode. This technique has been extensively employed at Thumba to study the equatorial mesospheric structure and its variations (Fig. 2).

3.2 Filter photometers

Absorption spectroscopy has been extensively used for the measurement of ozone distribution in the atmosphere. In fact one of the first ozone vertical distribution measurements up to mesospheric altitudes was obtained by Johnson et al. by flying two opposite looking solar UV spectrographs on an Aerobee rocket in June 1949. But most extensive measurements have been made using filter photometers in the UV (2500-3000 Å) region by using interference filters, solar blind phototubes and an electrometer amplifier with automatic gain switching. The three chambers are centred at 250 nm, 280 nm and 310 nm respectively with a band width of roughly 10 nm. They are selected so as to cover a wide range of altitude (10 km to about 70 km). For nighttime measurements moon is used as the source and since the fluxes are much smaller (about five orders of magnitude) photomultipliers are used instead of phototubes.

3.3 Absorption cell technique/Gas filter radiometry

A slight but ingenious variation of use of absorption spectroscopy for atmospheric science studies is the use of an absorption cell. The technique is most useful when the radiation intensities to be measured are weak. It is best illustrated by taking the case of nitric oxide measurements in the mesosphere and lower thermosphere. Nitric oxide concentrations can be estimated by measuring its fluorescence in the so called γ bands in the ultraviolet (2000-2500 Å) (Ref. 25). Even the strongest emissions the (1.0) and the (2.2) γ bands at 2148 and 2215 Å are weak and contamination due to Rayleigh scattered sunlight poses a serious problem. Attempts were made to measure

Fig. 3—Reference ozone profile for the equatorial region based on rocketborne optical ozonesonde measured at Thumba (8.5°N) (After Subbaraya & Jayaraman).
their intensities by rocket spectrographs. Tohmatsu and Iwagami developed a simple radiometer based on the absorption cell technique which is more convenient, gives a much larger throughput and enables more accurate measurements.

The instrument (Fig. 4) consists of a light baffle, a honeycomb collimator with a field of view of about 5°, and interference filter (100-150Å FWHM) and a solar blind photomultiplier with CsTe photocathode. Two fused silica cells, one filled with nitric oxide gas at ~200 Torr (the nitric oxide cell) and the other evacuated (blank cell), are alternately brought in front of the photomultiplier by a stepper motor assembly. The nitric oxide cell selectively absorbs some of the γ band emissions (Fig. 5) so the difference signal can be effectively used to estimate the nitric oxide concentrations. The radiometer needs laboratory calibration. It has been successfully used on rockets for estimating NO concentration in the 80-140 km altitude region. It has also been flown at Thumba and several measurements of the equatorial mesosphere have been made. The absorption cell technique has also been successfully used in several other planetary atmospheric investig-
ations, e.g. hydrogen/deuterium ratios in planetary atmospheres. The HALOE experiment flown on board the Upper Atmospheric Research Satellite (UARS) employed this technique for measurement of vertical profiles of HCl, HF, CH₄ and NO (Ref. 30).

4 Airglow measurements

Airglow emissions have been extensively used for study of the gross features of the atmospheric structure and dynamics. The oxygen 6300Å and 5577Å emissions for the thermosphere, OH Michel bands in the near infrared, sodium 5896Å and O₁Δg (1.27 μ) emissions for the mesosphere are some of the more commonly used emissions because of their larger intensities. With the advent of rockets it has become possible to measure their emission profiles in the atmosphere and to quantitatively study and understand in detail the emission mechanisms and also to study several aspects of atmospheric chemistry and dynamics. Extensive studies of thermospheric structure and dynamics have been based on the oxygen 6300Å and 5577Å airglow. The earliest measurements were from the OGO-4 and OGO-6 satellites. These were followed by more sophisticated instrumentation such as the Visual Airglow Experiment on Atmospheric Explorer Satellites and the high resolution Fabry Perot interferometer with a sophisticated Imaging Detector (IPD) flown on the Dynamic Explorer Satellites. The most extensive application in the ultraviolet has been in measurement of the Mg II doublet around 2800Å which can be used to study lower thermospheric dynamics. Using a 25 cm Ebert Fatsies monochromator on the OGO-4 satellite, Barth and coworkers detected the Mg II emission from the data of the ESRO TDI satellite ultraviolet telescope which was essentially meant for astronomical studies. Systematic measurements of the Mg II emissions and study of several features of the lower thermospheric dynamics including equatorial enhancement were made from OGO satellite data.

The Na, O₁Δg and OH emissions are especially suited for study of mesospheric structure and dynamics. In a collaborative programme between PRL and Service d'Aeronomie an attempt was made to study the structure of the waves in the mesosphere by photographing the OH emissions using an image intensifier camera on Spacelab. Figure 6 shows the scheme of the instrument. An infrared image of the OH layer is produced on the photocathode of an image intensifier (Thomson 9304 microchannel version) using a fast Angenieux lens (f= 25 mm and aperture f/0.95) and a Wratten 88A infrared filter. The intensified image at the output screen is photographed using an Eclair 16 mm motor operated camera with a similar Angenieux lens. The Wratten 88A filter provides the lower wavelength cutoff for the observed emission (50% at 758 nm). The upper wavelength cutoff is provided by the S20 ER cathode of the image intensifier (900 nm). The camera and the low speed motor are operated by a timer. To protect the image intensifier from possible destruction due to over illumination caused by direct sunlight or from the sunlit terrestrial flux a shutter is activated by a pair of photocells. The shutter will remain open only when the flux received is below a predetermined level.

The entire system is enclosed in a cylindrical chamber pressurized with nitrogen. The instru-

![Fig. 6—Schematic diagram of an image intensifier camera system for the study of waves in the OH emitting layer (After Prakash et al.41).](image-url)
ment is retrieved after flight and the camera pictures are analysed in the laboratory using a densitometer and digital image processing techniques. Feasibility of the technique was demonstrated by ground-based measurements. Even though such an instrument was flown on Spacelab III, it gave very limited data. In a somewhat similar approach but using a TV camera, Taylor and co-workers have attempted a study of the height structure of gravity waves in the mesosphere by measuring the emissions from different height regions. These techniques have great potential for satellite applications but they have so far not been exploited.

In recent years there have been great technological improvements both in terms of instrumentation and detectors, e.g. image intensifiers and CCD cameras, tandem Fabry Perot interferometers. Most of them have been in use for ground-based observations and they are yet to be deployed on space platforms.

5 Satellite-based trace gas measurements—

Stratospheric chemistry

This has been one of the major developments on the space scene in the past two decades, an area in which optical instrumentation has played a fundamental role. The subject became extremely topical in the seventies due to the recognition of the ozone depletion problem. Most of the trace gases of interest in the stratospheric chemistry have well defined absorption features either in the UV or the IR part of the spectrum. Satellite measurements of their total abundances and their vertical distributions have been made using the so-called limb scanning technique. In the nadir looking mode one uses a slight variation of the technique in which solar radiation backscattered by the atmosphere is received by the satellite sensor at two or more wavelengths, one of which is strongly absorbed and the other less (or not) absorbed by the species under investigation. Generally multiple wavelength pairs are used for improved accuracy, corrections for scattering and other background effects, and altitude coverage. Beginning with the feasibility study by Dave and Mateer, extensive measurements of the global ozone distribution and its long-term variations have been made with the SBUV and TOMS instrument on Nimbus series of satellites. From a polar sun synchronous orbit the TOMS instrument made daily global ozone maps and more than two decades of continuous total ozone data are now available which have been used for extensive studies of various aspects of stratospheric chemistry, including the ozone depletion problem. Vertical profiles have been measured by the SAGE instrument which uses the limb scanning technique.

Apart from ozone the Nimbus series of satellites have given extensive data on several other trace gases. For many of the gases of interest in stratospheric chemistry the infrared wavelength region has been found to be much more profitable. The Nimbus 7 SAMS (Stratosphere and Mesosphere Sounder) instrument carried a limb scanning six channel infrared radiometer with a scanning mirror, folded telescope and cooled detector array (Mercury Cadmium Telluride detector) and gave extensive data on a number of trace gases apart from ozone and water vapour, for example CO, CH₄, N₂O, HNO₃ (Refs 51-53). Use of optical instrumentation for middle atmospheric studies, which started as a purely meteorological programme in the sixties with temperature and water vapour measurements on TIROS and Nimbus satellites, evolved into a full-fledged operational middle atmosphere programme in the eighties with the Nimbus and NOAA series of satellites. The launch of UARS (Upper Atmospheric Research Satellite) in September 1991 with a number of highly sophisticated optical instruments for middle and upper atmospheric research can be considered as the culmination of this phase of space science research. In addition to the active cavity radiometer ACRIM for total solar flux measurements, an improved version of the Nimbus 7 Stratosphere and Mesosphere Sounder ISAMS and a microwave limb sounder, the UARS carried a number of highly sophisticated optical instruments for middle and upper atmospheric measurements. They are an ultraviolet solar spectral, irradiance monitor SUSIM for solar spectrum measurements, a small UV grating spectrometer called SOLSTICE to provide absolute calibration in the UV (1150-4400 Å), a Cryogenic Limb Array Etalon Spectrometer CLAES operating in the 3.5-12.7 μ range for measurement of atmospheric temperatures and several trace gases which include the radical species. The HALOE experiment employs gas filled pressure modulated cells (gas correlation spectroscopy) for study of halogen species CH₃ and CO, a triple etalon Fabry Perot interferometer HRDI (High Resolution Doppler Interferometer) for measurement of temperatures and winds at mesospheric altitudes, and a Michelsen interferometer for measurement of OH and wind fields in the mesosphere and lower thermosphere.
In spite of some early setbacks in the initial phases of the satellite orbit due to problems connected with the onboard power systems, the overall mission has been highly successful. A large amount of data has been collected for about two years and the potential of this data for use in Global Stratospheric Monitoring programme has been described by Gellman et al.\textsuperscript{54} and Taylor et al.\textsuperscript{55} The UARS mission marks the beginning of a new era for studying aeronomy and atmospheric sciences using optical instrumentation. Currently several new programmes are in progress (or are being planned) with even better instrumentation. High resolution Michelson interferometers are being planned for Earth Resources Satellite missions. The ERS 2 Global Ozone Monitoring experiment planned for 1995-96 time frame has scanning spectrometer in the $240-760$ nm wavelength region for ozone, NO, species, SO$_2$, H$_2$O, ClO, BrO, CH$_3$O, ClO$_2$, etc. European Space Agency has several exciting programmes for the later half of the nineties. A Scanning Imaging Absorption Spectrometer for Atmospheric Chartography SCIAMACHY, which has potential for a wide range of applications in astronomy and atmospheric sciences, meteorology, oceanographic and other remote sensing applications, is being designed for flying on a European Polar Platform\textsuperscript{56} and goes far beyond TOMS, SAGE and SME instruments in so far as instrument concept is concerned. A stellar occultation experiment in the UV, visible and near IR bands is also being planned by ESA towards the end of this decade which can contribute to the Global Ozone Monitoring Programme by providing data on vertical profiles of aerosols and several related trace gases. The instrument is capable of high altitude resolution and accuracy.

6 The Indian scene
Even though optical instruments have been extensively used on rockets and satellites all over the world and many exciting and pioneering results have been obtained, the situation has not been very bright on the Indian scene. The activity has been rather limited. Narrow band UV filter photometers have been extensively used for ozone profile measurements\textsuperscript{22,23}, multiwavelength radiometers for aerosol measurements\textsuperscript{57,58}, Lyman-\(\alpha\) and gas gain ion chambers for O$_2$ measurements in the mesosphere and lower thermosphere\textsuperscript{17}, \(\gamma\)-band photometers with the absorption cell technique for nitric oxide measurements\textsuperscript{29}, and airglow photometer for 5577Å emission and atomic oxygen studies\textsuperscript{59}. These have all been on rockets.

The first Indian satellite Aryabhata launched in 1975 carried a pair of ion chambers for mapping the geo-coronal hydrogen and oxygen emissions\textsuperscript{60}, but it did not yield any results. Similarly there was an unsuccessful collaborative programme with Service d'Aeronomie of France to study the mesospheric OH emissions from Spacelab. Both these gave the Indian scientists opportunities to satellite-based optical instrumentation for atmospheric science research. But this experience could not be exploited for scientific results. There have been no further opportunities to pursue these or related investigations in the succeeding years.

In recent years several sophisticated optical instruments like Fabry Perot spectrometer\textsuperscript{61,62}, multiwavelength dayglow photometer\textsuperscript{63}, image intensifier and CCD camera systems\textsuperscript{64} have been successfully built and are in operational use for aeronomical investigations. These have potential for deployment from space platforms. Further, satellite remote sensing programmes have developed instrumentation, infrastructure and satellite system interfaces which are adoptable for atmospheric science research. In fact the border line between remote sensing for applications research and middle atmospheric science research is rather thin as evidenced by the efforts of NASA in the seventies and the eighties. With a little bit of effort it is possible to adopt the development in one field to another. With the recent success of the PSLV-D2 mission there is promise of availability of suitable platforms. With some initiative on the part of scientific groups and support from the organizations it should be possible to bring these different expertises together for a satellite programme for aeronomy and atmospheric science research using optical instrumentation.

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References
8 Neupert W M, Behring W E & Lindsay J C, Space Res (North-Holland, Amsterdam, Netherlands), 4 (1964) 749.
25 Barth C A, J Geophys Res (USA), 69 (1964) 3301.
31 Chandra S, Reed E I, Troy B E & Blamont J E, J Geophys Res (USA), 78 (1973) 4630.
32 Reed E I, Fowler W B & Blamont J E, J Geophys Res (USA), 78 (1973) 5658.
37 Anderson J G & Barth C A, J Geophys Res (USA), 76 (1971) 3723.
38 Boksenden A & Gerard J C, J Geophys Res (USA), 78 (1973) 4641.
59 Kulkarni P V, J Geophys Res (USA), 81 (1976) 3640.