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# MILLIMETER WAVE OBSERVATIONS OF STRATOSPHERIC OZONE AT APATITY, KOLA PENINSULA DURING SOLVE-2 CAMPAIGN IN WINTER 2002/2003

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**Abstract.** A microwave ground-based radiometer has been developed for long-term measurements of stratospheric ozone profiles at polar latitudes. The instrument installed in Apatity, Russia (67°N) operates in the framework of the Russian atmospheric station. The instrument detects an ozone spectral line at 101.736 GHz, enabling a retrieval of ozone profiles from 20 to 60 km. During winter 2002/2003 the microwave radiometer was successfully operating on 80 days. A strong ozone depletion was registered during the period 1-26 December 2002 within the altitude range 25-60 km.

## Introduction

The results of ground-based microwave measurements of stratospheric ozone at heights from 20 km to 60 km at polar latitude during winter 2002/2003 SOLVE-2 are presented. The SAGE-III Ozone Loss and Validation Experiment (SOLVE) is a measurement campaign designed to examine the processes that control polar to mid latitude stratospheric ozone level. The measurements were made in the Arctic high-latitude region in winter, using NASA DC-8 aircraft as well as balloon platforms and ground-based instruments. The mission will also acquire correlative data needed to validate the Stratospheric Aerosol and Gas Experiment (SAGE) III satellite measurements that will be used to quantitatively access the high-latitude ozone loss.

## Method

The observations were performed with the ground-based millimeter wave instrument in Apatity, Kola Peninsula (67°N, 35°E), measuring the thermal emission line in the purely rotational spectrum $4_{1,3} - 4_{0,4}$ transition of ozone at the resonance frequency of 101736.76 MHz. This observation site was chosen because of the specific climatic conditions. The polar vortex is rather frequently located above Apatity, which is essential for observing disturbed stratospheric chemistry. The instrument consists of a millimeter wave uncooled receiver and multichannel spectrometer. The receiver has a single sideband noise temperature of about 3000 K. The local oscillator is a carcinotron (backward-wave tube) with the frequency locked to 102486.76 MHz. The receiver includes a filter (quasi-optical system), which suppresses mixer image sideband response by 15 dB. The spectrometer represents the filter system (20 spectral channels) with 150 MHz complete band for analysis and a variable frequency resolution of 1 – 15 MHz. The parameters of this instrument makes it possible to perform an ozone remote sensing (altitude interval 20-60 km) with a time resolution of 1 hour. The instrument, observation technique and calibration method are described by Dyomkin et al. [1]. With this technique, the observations do not depend on sunlight, may be conducted through a moderately thick higher cloud cover, and are not significantly affected by aerosols.

## Measurements and retrieval

The measurements of spectra of atmospheric emission were carried out both by the method of variation of zenith distance and by the method of its calibration on hot and cold reference loads. To retrieve $O_3$ vertical profiles from measured spectra, we have used the model-fitting method as described by de La Noë et al [2]. As retrieval procedure, model vertical distributions of pressure and temperature [3] as well as real data obtained as results of balloon measurements were used. Uncertainty of retrieval depends on radio measurement errors and systematic artifacts of the ozone spectrum and generally is about 20% at altitude region from 20 km up to 60 km.

## Discussion

Preliminary ozone density data versus time and altitude for the period of November 2002 through March 2003 are presented in Fig. 1. Two bottom panels in Fig. 1 also show temperature values at pressure levels 20 hPa ($T_{20}$) and 10 hPa ($T_{10}$), which were taken from Internet site (http://wesley.wwb.noaa.gov). The preliminary analysis of microwave data has shown that from the middle of November 2002 to the beginning of March 2003 at heights from 20 km to 30 km was observed the reduced ozone content. In November-December 2002 and in January 2003 except for the third decade the average ozone density at height 25 km was ~ $2 \cdot 10^{12}$ $cm^{-3}$ ( see Table I ). From February 1 to March 6, 2003 the average ozone density at height of 25 km was about $2.3 \cdot 10^{12}$ $cm^{-3}$. For comparison, in winter 1999/2000 (SOLVE I) [4] this value was equal to $(2.35 \pm 0.11) \cdot 10^{12}$ $cm^{-3}$, $(2.94 \pm 0.48) \cdot 10^{12}$ $cm^{-3}$ and $(3.25 \pm 0.64) \cdot 10^{12}$ $cm^{-3}$ for January, February and March, respectively. Microwave observations in December 2002 revealed the lowest ozone density of $(1.99 \pm 0.23) \cdot 10^{12}$ $cm^{-3}$. Thus in December, 2000 the average ozone density at 25 km was about $(2.80 \pm 0.33) \cdot 10^{12}$ $cm^{-3}$ and in December, 1987 – $(2.13 \pm 0.21) \cdot 10^{12}$ $cm^{-3}$. This finding, evidently, can be explained by the fact that during the major part of observational period in winter season 2002/2003 Apatity was inside the polar stratospheric cyclonic vortex, which was rather intensive and well pronounced (http://wvms.nrl.navy.mil/POAM/solve2). Only in the third decade of January, 2003, when due to enhanced wave

activity the vortex was partially disturbed and removed from the area of Kola Peninsula, here was observed strong stratospheric warming (the temperature increase at 20 hPa was equal to 40º). This warming was accompanied by increase in ozone density at 25 km more than by factor 2 (from $2 \cdot 10^{12}$ up to $4 \cdot 10^{12}$ $cm^{-3}$). It is necessary to emphasise that the upper boundary of ozone increasing extended to 40 km. At this level the ozone density changed from $(2.4 \pm 0.35) \cdot 10^{11}$ to $(3.09 \pm 0.26) \cdot 10^{11}$ $cm^{-3}$. In this period Apatity appeared to be outside the polar cyclone. Let's note that in the observational period at the pressure level of 10 hPa three waves of warming were detected (see Fig.1), and the maximum increase of temperature at the end of December achieved 50º. But a positive correlation between ozone and these temperature variations was clearly seen only during the third wave at the end of January - beginning of February.

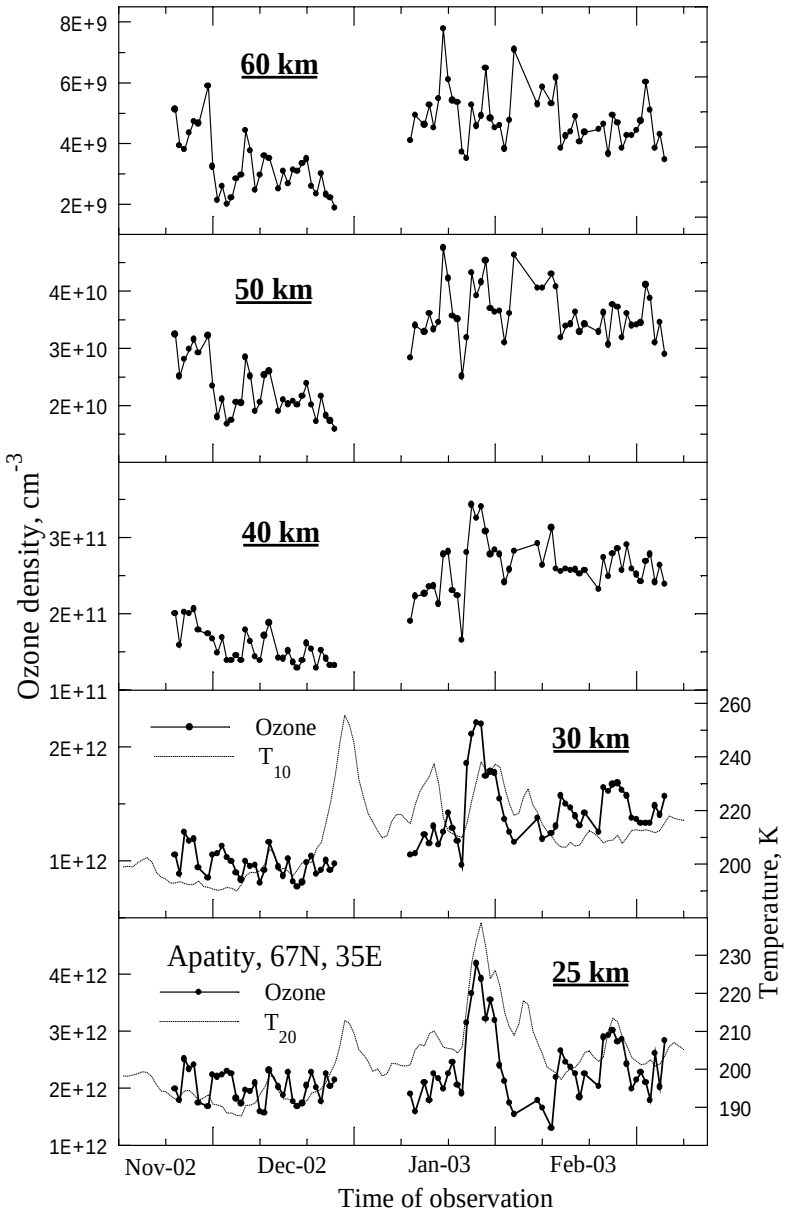


Fig. 1

It is interesting to follow the ozone behavior at higher levels. For one month, i.e. from the middle of January to the middle of February, at heights larger than 40 km fluctuations of the ozone content associated with the global stratospheric warming are clearly pronounced. The signatures of this warming in the upper layers are seen in Fig. 1. Unfortunately, we have no data of temperature sounding at heights larger than 30 km. However, it is evident that there was a significant increase of ozone content in the upper stratosphere in January - February as compared with December. In our opinion, this increase is caused by meridian circulation that led to ozone transport from middle latitudes to the upper stratosphere of the polar region. The descending airflow associated with the vertical compo- nent of this circulation, apparently, caused significant temperature disturbances and corresponding ozone fluctuations. Maps of the Arctic vortex position given in Internet site (http://wvms.nrl.navy.mil/POAM/solve2) indicate that at this time strong distortions of the vortex and even its partial disruption caused by activation of a planetary wave took place (http://hyperion.gsfc.nasa.gov/Data_services/met/ann_data.html).

In the second half of February appreciable variations of the ozone content at heights 20 – 30 km were registered again. Increases of $O_3$ from February 12 to February 14 and from February 21 to February 26 (see Table I and Fig. 1) were again coincident with strengthening of wave activity and cyclon vortex disruption into two parts. At the end of February Apatity appeared to be outside the vortex. In this case, typical is intensive air mixing between high and middle latitudes. The above mentioned stratospheric ozone variability during disruption of the vortex is evidently caused by intrusion of air masses into the polar region from outside.

## Conclusions

All the above results of microwave measurements are consistent with the increase of the ozone content during disruption of the winter circumpolar vortex followed by stratospheric warming. The observations during winter season 2002/2003 have shown that the regions located inside the Arctic vortex are characterized by the reduced ozone

content as compared to those outside the vortex. The data presented in Fig. 1 testify that from the middle of November, 2002 to the middle of February, 2003, except for the last decade of January, when Apatity was outside the vortex, the gradual decrease of the ozone density at 25 km from $2 \cdot 10^{12}$ $cm^{-3}$ to $1{,}5 \cdot 10^{12}$ $cm^{-3}$ occurred. We note that according to the POAM III data [5], given in the site (http://wvms.nrl.navy.mil/POAM/solve2), during December, first half of January and at the beginning of February 2003, at the temperature level of 500K polar stratospheric clouds (PSC) were systematically observed inside the vortex. It should be kept in mind that in December Apatity was inside the vortex, and stratospheric temperature here dropped below the threshold of PSC I type formation. Probably, the ozone decrease reported above is caused by chemical losses inside the polar stratospheric vortex.

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**Table I. Ozone number density (in mol/cm$^3$) at different heights and total ozone above 20 km (in Dobson Units).**
**Apatity (67°N, 35°E), Kola Peninsula. SOLVE-II mission (November-March 2002/2003)**

| Date | z = 25 km | z = 30 km | z = 40 km | z = 50 km | z = 60 km | $X_{O3}$ (z≥20km) |
|---|---|---|---|---|---|---|
| 22-11-2002 | 1.98E+12 | 1.05E+12 | 2.00E+11 | 3.24E+10 | 5.12E+09 | 101.5 |
| 23-11-2002 | 1.78E+12 | 8.85E+11 | 1.58E+11 | 2.51E+10 | 3.93E+09 | 91 |
| 24-11-2002 | 2.51E+12 | 1.25E+12 | 2.02E+11 | 2.80E+10 | 3.80E+09 | 124.6 |
| 25-11-2002 | 2.33E+12 | 1.17E+12 | 2.00E+11 | 2.98E+10 | 4.34E+09 | 117.4 |
| 26-11-2002 | 2.41E+12 | 1.19E+12 | 2.06E+11 | 3.15E+10 | 4.73E+09 | 122.7 |
| 27-11-2002 | 1.75E+12 | 9.34E+11 | 1.78E+11 | 2.92E+10 | 4.66E+09 | 90 |
| 29-11-2002 | 1.68E+12 | 8.49E+11 | 1.73E+11 | 3.22E+10 | 5.91E+09 | 89.4 |
| 30-11-2002 | 2.24E+12 | 1.05E+12 | 1.67E+11 | 2.34E+10 | 3.24E+09 | 112.4 |
| **Average** | **(2.08±0.31)** | **(1.05±0.14)** | **(1.85±0.17)** | **(2.89±0.31)** | **(4.47±0.78)** | **(106.1±14.0)** |
| 01-12-2002 | 2.20E+12 | 1.06E+12 | 1.49E+11 | 1.80E+10 | 2.14E+09 | 106.5 |
| 02-12-2002 | 2.23E+12 | 1.13E+12 | 1.68E+11 | 2.11E+10 | 2.59E+09 | 108.1 |
| 03-12-2002 | 2.30E+12 | 1.03E+12 | 1.39E+11 | 1.67E+10 | 1.99E+09 | 112.2 |
| 04-12-2002 | 2.25E+12 | 9.97E+11 | 1.39E+11 | 1.75E+10 | 2.20E+09 | 111 |
| 05-12-2002 | 1.82E+12 | 8.95E+11 | 1.45E+11 | 2.05E+10 | 2.84E+09 | 90.8 |
| 06-12-2002 | 1.73E+12 | 8.33E+11 | 1.38E+11 | 2.04E+10 | 2.96E+09 | 87.5 |
| 07-12-2002 | 1.97E+12 | 9.94E+11 | 1.79E+11 | 2.84E+10 | 4.42E+09 | 101 |
| 08-12-2002 | 1.94E+12 | 9.52E+11 | 1.64E+11 | 2.51E+10 | 3.76E+09 | 98.6 |
| 09-12-2002 | 2.09E+12 | 9.64E+11 | 1.43E+11 | 1.90E+10 | 2.47E+09 | 103.7 |
| 10-12-2002 | 1.58E+12 | 8.07E+11 | 1.38E+11 | 2.05E+10 | 2.97E+09 | 79.4 |
| 11-12-2002 | 1.56E+12 | 9.19E+11 | 1.71E+11 | 2.53E+10 | 3.61E+09 | 79.3 |
| 12-12-2002 | 2.31E+12 | 1.16E+12 | 1.88E+11 | 2.60E+10 | 3.52E+09 | 114.4 |
| 14-12-2002 | 2.02E+12 | 9.43E+11 | 1.42E+11 | 1.90E+10 | 3.01E+09 | 100.6 |
| 15-12-2002 | 1.87E+12 | 8.64E+11 | 1.41E+11 | 2.10E+10 | 3.08E+09 | 95.9 |
| 16-12-2002 | 2.27E+12 | 1.02E+12 | 1.51E+11 | 2.02E+10 | 2.66E+09 | 114 |
| 17-12-2002 | 1.76E+12 | 8.18E+11 | 1.36E+11 | 2.08E+10 | 3.14E+09 | 90.7 |
| 18-12-2002 | 1.68E+12 | 7.69E+11 | 1.29E+11 | 2.01E+10 | 3.09E+09 | 87.5 |
| 19-12-2002 | 1.73E+12 | 8.11E+11 | 1.38E+11 | 2.17E+10 | 3.35E+09 | 89.4 |
| 20-12-2002 | 2.04E+12 | 9.79E+11 | 1.61E+11 | 2.38E+10 | 3.49E+09 | 103.2 |
| 21-12-2002 | 2.28E+12 | 1.04E+12 | 1.53E+11 | 2.01E+10 | 2.60E+09 | 112.9 |
| 22-12-2002 | 2.01E+12 | 8.78E+11 | 1.28E+11 | 1.72E+10 | 2.33E+09 | 101.6 |
| 23-12-2002 | 1.76E+12 | 9.12E+11 | 1.52E+11 | 2.16E+10 | 3.01E+09 | 88 |
| 24-12-2002 | 2.26E+12 | 9.98E+11 | 1.41E+11 | 1.82E+10 | 2.32E+09 | 112.8 |
| 25-12-2002 | 2.03E+12 | 9.13E+11 | 1.32E+11 | 1.73E+10 | 2.23E+09 | 101.5 |
| 26-12-2002 | 2.15E+12 | 9.73E+11 | 1.32E+11 | 1.59E+10 | 1.88E+09 | 105.1 |
| **Average** | **(1.99±0.23)** | **(9.46±0.98)** | **(1.48±0.15)** | **(2.06±0.30)** | **(2.87±0.60)** | **(99.8±10.5)** |
| 11-01-2003 | 1.89E+12 | 1.05E+12 | 1.90E+11 | 2.83E+10 | 4.10E+09 | 95.5 |
| 12-01-2003 | 1.58E+12 | 1.06E+12 | 2.23E+11 | 3.40E+10 | 4.93E+09 | 89.3 |
| 14-01-2003 | 2.10E+12 | 1.23E+12 | 2.26E+11 | 3.29E+10 | 4.62E+09 | 105.9 |
| 15-01-2003 | 1.78E+12 | 1.15E+12 | 2.35E+11 | 3.60E+10 | 5.27E+09 | 92.6 |
| 16-01-2003 | 2.25E+12 | 1.30E+12 | 2.36E+11 | 3.33E+10 | 4.52E+09 | 114.1 |
| 17-01-2003 | 2.16E+12 | 1.14E+12 | 2.13E+11 | 3.46E+10 | 5.47E+09 | 110.9 |
| 18-01-2003 | 1.98E+12 | 1.25E+12 | 2.78E+11 | 4.75E+10 | 7.77E+09 | 105 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 19-01-2003 | 2.26E+12 | 1.42E+12 | 2.81E+11 | 4.22E+10 | 6.09E+09 | 116.3 |
| 20-01-2003 | 2.46E+12 | 1.28E+12 | 2.30E+11 | 3.57E+10 | 5.42E+09 | 125.4 |
| 21-01-2003 | 2.06E+12 | 1.17E+12 | 2.24E+11 | 3.51E+10 | 5.34E+09 | 105.4 |
| 22-01-2003 | 1.91E+12 | 9.56E+11 | 1.65E+11 | 2.51E+10 | 3.73E+09 | 97.1 |
| 23-01-2003 | 3.14E+12 | 1.85E+12 | 2.80E+11 | 3.19E+10 | 3.52E+09 | 151.1 |
| 24-01-2003 | 3.65E+12 | 2.11E+12 | 3.43E+11 | 4.32E+10 | 5.27E+09 | 178.8 |
| 25-01-2003 | 4.18E+12 | 2.21E+12 | 3.26E+11 | 3.92E+10 | 4.58E+09 | 201 |
| 26-01-2003 | 3.91E+12 | 2.20E+12 | 3.41E+11 | 4.15E+10 | 4.91E+09 | 189.2 |
| 27-01-2003 | 3.21E+12 | 1.74E+12 | 3.08E+11 | 4.53E+10 | 6.48E+09 | 161.2 |
| 28-01-2003 | 3.55E+12 | 1.78E+12 | 2.78E+11 | 3.70E+10 | 4.83E+09 | 174.6 |
| 29-01-2003 | 3.19E+12 | 1.77E+12 | 2.84E+11 | 3.63E+10 | 4.51E+09 | 155.8 |
| 30-01-2003 | 2.40E+12 | 1.54E+12 | 2.78E+11 | 3.65E+10 | 4.59E+09 | 121.1 |
| 31-01-2003 | 2.12E+12 | 1.36E+12 | 2.41E+11 | 3.10E+10 | 3.82E+09 | 106.3 |
| **Average** | **(2.59±0.76)** | **(1.47±0.39)** | **(2.59±0.47)** | **(3.63±0.54)** | **(4.99±0.97)** | **(129.8±34.4)** |
| 01-02-2003 | 1.74E+12 | 1.25E+12 | 2.58E+11 | 3.61E+10 | 4.77E+09 | 92.2 |
| 02-02-2003 | 1.54E+12 | 1.16E+12 | 2.82E+11 | 4.63E+10 | 7.08E+09 | 86.2 |
| 07-02-2003 | 1.79E+12 | 1.37E+12 | 2.92E+11 | 4.06E+10 | 5.29E+09 | 97.5 |
| 08-02-2003 | 1.65E+12 | 1.19E+12 | 2.64E+11 | 4.05E+10 | 5.86E+09 | 89.3 |
| 10-02-2003 | 1.30E+12 | 1.24E+12 | 3.13E+11 | 4.29E+10 | 5.32E+09 | 80 |
| 11-02-2003 | 2.18E+12 | 1.30E+12 | 2.59E+11 | 4.08E+10 | 6.17E+09 | 112.4 |
| 12-02-2003 | 2.66E+12 | 1.57E+12 | 2.55E+11 | 3.19E+10 | 3.85E+09 | 130.3 |
| 13-02-2003 | 2.46E+12 | 1.50E+12 | 2.59E+11 | 3.38E+10 | 4.24E+09 | 122.5 |
| 14-02-2003 | 2.36E+12 | 1.46E+12 | 2.57E+11 | 3.42E+10 | 4.39E+09 | 118.1 |
| 15-02-2003 | 2.25E+12 | 1.39E+12 | 2.58E+11 | 3.63E+10 | 4.89E+09 | 114.2 |
| 16-02-2003 | 1.84E+12 | 1.31E+12 | 2.52E+11 | 3.29E+10 | 4.06E+09 | 95.8 |
| 17-02-2003 | 2.25E+12 | 1.42E+12 | 2.57E+11 | 3.42E+10 | 4.37E+09 | 113.5 |
| 20-02-2003 | 2.03E+12 | 1.25E+12 | 2.32E+11 | 3.29E+10 | 4.47E+09 | 103 |
| 21-02-2003 | 2.89E+12 | 1.64E+12 | 2.74E+11 | 3.62E+10 | 4.64E+09 | 142.9 |
| 22-02-2003 | 2.92E+12 | 1.61E+12 | 2.49E+11 | 3.06E+10 | 3.60E+09 | 141.6 |
| 23-02-2003 | 3.01E+12 | 1.67E+12 | 2.79E+11 | 3.77E+10 | 4.92E+09 | 148.4 |
| 24-02-2003 | 2.81E+12 | 1.68E+12 | 2.86E+11 | 3.72E+10 | 4.68E+09 | 139.3 |
| 25-02-2003 | 2.86E+12 | 1.62E+12 | 2.57E+11 | 3.19E+10 | 3.85E+09 | 139.2 |
| 26-02-2003 | 2.42E+12 | 1.57E+12 | 2.90E+11 | 3.60E+10 | 4.26E+09 | 124.5 |
| 27-02-2003 | 1.99E+12 | 1.37E+12 | 2.59E+11 | 3.40E+10 | 4.25E+09 | 102.7 |
| 28-02-2003 | 2.14E+12 | 1.36E+12 | 2.51E+11 | 3.41E+10 | 4.44E+09 | 108.3 |
| **Average** | **(2.24±0.48)** | **(1.42±0.16)** | **(2.66±0.18)** | **(3.62±0.39)** | **(4.73±0.81)** | **(114.4±20.0)** |
| 01-03-2003 | 2.28E+12 | 1.33E+12 | 2.42E+11 | 3.44E+10 | 4.74E+09 | 114.5 |
| 02-03-2003 | 2.10E+12 | 1.33E+12 | 2.69E+11 | 4.11E+10 | 6.02E+09 | 109 |
| 03-03-2003 | 1.79E+12 | 1.33E+12 | 2.78E+11 | 3.88E+10 | 5.10E+09 | 96.2 |
| 04-03-2003 | 2.61E+12 | 1.48E+12 | 2.41E+11 | 3.09E+10 | 3.84E+09 | 127.9 |
| 05-03-2003 | 2.02E+12 | 1.40E+12 | 2.64E+11 | 3.46E+10 | 4.31E+09 | 104.2 |
| 06-03-2003 | 2.84E+12 | 1.56E+12 | 2.38E+11 | 2.90E+10 | 3.46E+09 | 136.8 |
| **Average** | **(2.27±0.36)** | **(1.40±0.09)** | **(2.55±0.15)** | **(3.48±0.42)** | **(4.58±0.84)** | **(114.8±13.8)** |

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