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COMMITTEE ON THE PEACEFUL USES
OF OUTER SPACE

ENVIRONMENTAL EFFECTS OF SPACE ACTIVITIES

Report submitted by the Committee on Space Research and the International Astronautical Federation

Note by the Secretariat

The report annexed hereto is submitted to the Scientific and Technical Sub-Committee of the Committee on the Peaceful Uses of Outer Space by the Committee on Space Research (COSPAR) of the International Council of Scientific Unions (ICSU) and the International Astronautical Federation (IAF) in response to an invitation from the Committee.

This invitation was based on a recommendation of the Working Group of the Whole established by the Scientific and Technical Sub-Committee at its twenty-fourth session, in 1987, to evaluate the implementation of the recommendations of the Second United Nations Conference on the Exploration and Peaceful Uses of Outer Space (UNISPACE 82). The report of the Working Group of the Whole (A/AC.105/383 and Corr.1, annex II), which was adopted by the Scientific and Technical Sub-Committee, contained a number of recommendations for studies. These recommendations were approved by the Committee on the Peaceful Uses of Outer Space 1/ and were subsequently endorsed by the General Assembly in its resolution 42/68 of 2 December 1987.

The present study was undertaken in accordance with paragraph 13 (d) of the report of the Working Group of the Whole, which reads as follows:

> "The Committee should, within existing resources, taking into account the study on environmental effects of space activities prepared by COSPAR (A/AC.105/334), invite COSPAR and IAF to undertake a follow-up study on the environmental effects of space activities, with particular emphasis on space debris."

A preliminary status report on the question of space debris (A/AC.105/403) was submitted by COSPAR to the Scientific and Technical Sub-Committee at its twenty-fifth session, in 1988. That preliminary report is superseded by the present report, prepared by S. J. Bauer on behalf of COSPAR and by L. Perek on behalf of IAF.

Notes

1/ See Official Records of the General Assembly, Forty-second session, Supplement No. 20 (A/42/20), para. 27.

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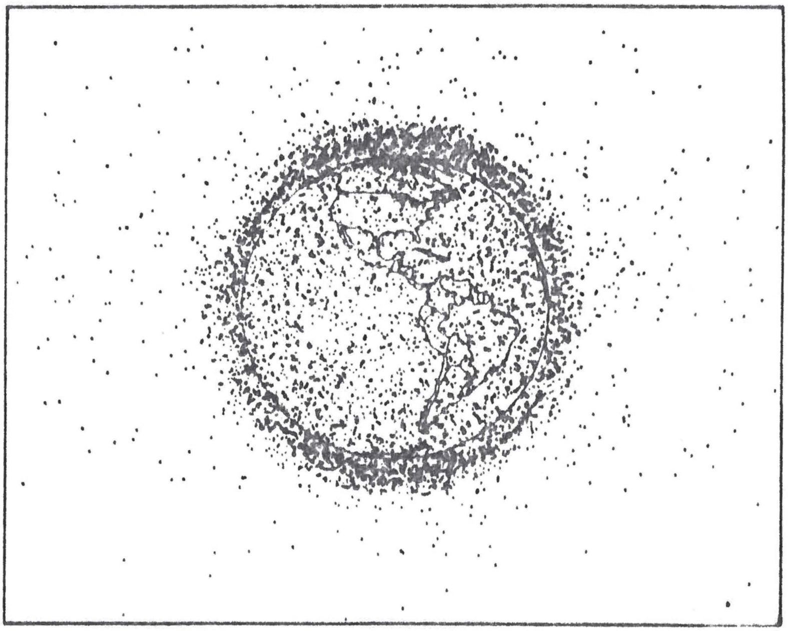
Annex

COSPAR
Committee on Space Research
established by the ICSU

IAF
International
Astronautical Federation

ENVIRONMENTAL EFFECTS OF SPACE ACTIVITIES

A Report
prepared by COSPAR and IAF for the
United Nations
Scientific and Technical Sub-Committee
of the
Committee on the Peaceful Uses of Outer Space



November 1988

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Title page Figure 1 - Snapshot of all trackable space objects at 00:00 Universal Time of 1 January 1987. Near Earth view. Produced by Teledyne Brown Engineering. See [1].

1 Foreword

The Committee on the Peaceful Uses of Outer Space, at its thirtieth session in June 1988, taking into account the study of Environmental Effects of Space Activities, prepared by COSPAR, A/AC. 105/334 of 23 November 1984, endorsed the request of the Scientific and Technical Sub-Committee, to invite COSPAR and the International Astronautical Federation (IAF) to undertake a follow-up study on the environmental effects of space activities, with particular emphasis on space debris. In response to that request, the present report has been prepared by S.J. Bauer on behalf of COSPAR and by L. Perek on behalf of the IAF. The report has been considered and approved by the COSPAR Bureau and by the IAF Bureau.

The Scientific and Technical Sub-Committee has had before it in the past several documents touching on the present topic: Mutual Relations of Space missions, A/AC.105/261 of 7 December 1979, Study on the Dynamics of Space Objects, A/AC.105/259 of 11 January 1980 and Add. 1 of 14 January 1980, Impact of Space Activities on the Earth and Space Environment, A/CONF. 101/BP/4 of 30 January 1981 (a background paper to the conference UNISPACE 1982) and the above mentioned study by COSPAR.

This study has been elaborated on the basis of past and present space activities. Should future space activities continue approximately at the same extent and style, the data of this study may stay valid for a few years. Should, however, future space activities increase to a multiple of the present level or should new propulsion methods be introduced or new applications of space science and technology implemented, an updating of this study would become necessary. Also progress in science, such as a better understanding of the influence of solar activity on the space environment, or progress in technology, such as detecting space debris of small sizes, may require a re-evaluation of some results presented below.

2 Concern of the International Scientific Community

The present study deals with effects of space activities on the space environment, on the various layers of the atmosphere as well as on the ground. Some of these effects constitute potentially harmful environmental pollution. Although the level of space activities has been more or less constant in the last several years, some environmental effects are steadily increasing. Many scientists are of the opinion that such effects may become, or have already become, irreversible and that preventive measures have to be adopted at the present time in order to avert difficult problems in the future. It seems that preventive measures are technically feasible while future remedies, such as cleaning of outer space, are beyond the possibilities of present science and technology.

Among those concerned about the pollution of outer space by debris are astronomers because photographs of faraway celestial objects frequently record traces of space objects. Non-repeatable observations may thus be lost to science and the progress of astronomy slowed down. E.g., specular reflections from artificial space objects may be confused with transient optical emissions of gamma-ray sources in supernova remnants [1]. Also the danger of space debris to expensive scientific missions is realized: the detectors on the Hubble Space Telescope may be damaged or degraded and its guidance sensors confused. There is approximately a one percent chance that the Space Telescope will be destroyed by a collision with a large piece of man-made space debris during its projected lifetime [2].

2 CONCERN OF THE INTERNATIONAL SCIENTIFIC COMMUNITY

The International Astronomical Union, an organization of some 6000 professional astronomers, adopted at its General assembly in Delhi, India, in 1985, the following resolution [3]:

The International Astronomical Union,

- *noting with grave concern* the dramatically increasing uses of space for scientific or other purposes and the accompanying contamination of space that adversely affects astronomical observations from the ground and from space,
- *re-affirms* its previous resolutions bearing on the uses of space,
- *maintains* that no group has the right to change the Earth's environment in any significant way without full international study and agreement, and
- *urges* that all national representatives bring this concern to the notice of adhering organizations and space agencies in their countries.

The matter was under discussion at the General Assembly of the IAU in Baltimore, USA, in August 1988:

The XX General Assembly of the IAU,

- *noting with grave concern* the increasing impact of light pollution, radio frequency interference, space debris, and other environmental factors that adversely affect observing conditions from the ground and in space;
- *re-affirms* the special importance of the resolutions adopted by previous General Assemblies that relate to the protection of observatories (ground-based and in space) and of observing conditions ... ;
- *strongly urges*
  1. that all astronomers request civil authorities and others in their countries to implement solutions to preserve the quality of observing conditions,
  2. that all national organizations bring these concerns to the notice of adhering organizations, space agencies, and others in their countries;
- *notes with special appreciation* those agencies, communities, organizations, and individuals who have become aware of the issues and have begun to help; and
- *encourages* all others, everywhere, to become aware of the need to minimize the impact on the environment of light pollution, radio frequency interference, and space debris, which are causing increasingly severe impact on observing conditions for astronomy and which will continue to compromise mankind's view of the Universe; and
- *requests* through ICSU that SCOPE (Scientific Committee on Problems of the Environment) should study the nature and extent of this threat and advise the IAU of its findings.

An IAU Colloquium on Light Pollution, Radio Interference and Space Debris was held in Washington, D.C., USA, in August 1988.

2 CONCERN OF THE INTERNATIONAL SCIENTIFIC COMMUNITY

Space pollution and, in particular, artificial space debris are being closely followed by COSPAR and IAF with a view to maintaining safety of space operations as well as protecting the environment.

COSPAR established a Panel on Potentially Environmentally Detrimental Activities in Space (PEDAS) and at the three most recent COSPAR Plenary Meetings, held in 1984, 1986 and 1988, special workshops have been devoted to the study of orbital debris [4]. In 1984, COSPAR adopted the following decision [5]:

> COSPAR,
>
> - *noting* the increasing population of satellites, space vehicles, explosion fragments, and propulsion by-products in the near-Earth environment, and
> - *considering* the probable collisions of bodies in this population and the consequent increase of the number of uncontrolled objects in space generated from such collisions, and its effect on the future utilization of space, and
> - *noting* the proposed inclusion of a Workshop in the 1986 COSPAR Meeting,
> - *recommends* that encouragement be given to studies of the satellite, space vehicle and artificial particulate population of the near-Earth environment, and
> - *recommends* that the international Symposium on Space Safety and Rescue (IAF/IAA forthcoming meeting on 8-13 October 1984 at Lausanne, Switzerland) be informed of COSPAR's concern in these matters.

At the IAF Congresses, space debris and space safety have been considered for many years in the framework of the IAA (International Academy of Astronautics) Symposia on Safety and Rescue [6]. Legal aspects of the environmental impact of space activities have been discussed at several Colloquia and Round Table Discussions of the International Institute of Space Law [7].

The European Space Agency (ESA) organized a Workshop on the Re-entry of Space Debris in 1985 [8] and in 1988 set up an ESA Space Debris Working Group, chaired by Prof. Dr. D. Rex, to prepare a Space Debris Report due to appear by the end of 1988 [9].

The Institute of Air and Space Law of the Cologne University organized an international colloquium on the Environmental Aspects of Activities in Outer Space - State of the Law and Measures for Protection, held in Cologne, Fed. Rep. Germany, in 1988 [10].

On the national level, discussions of scientific, technical and legal aspects of space debris took place on many occasions. A few examples: The American Institute of Aeronautics and Astronautics adopted a position paper on space debris in 1981 [11]. NASA organized a conference on orbital debris [12] and the U.S. Department of Defense conducted a study in 1986 examining the most currently available data derived from objects returned from and observed in space [13]. A monograph by N.L. Johnson and D.S. McKnight on Artificial Space Debris appeared in 1987 [14] and a quarterly, Orbital Debris Monitor [15], started to appear in 1988.

The above selection from current literature shows that the pollution of outer space and space debris in particular have been recognized as important topics by the scientific, technical and legal communities. Relevant questions are being discussed at national and international meetings and results are published in specialist as well as wide-circulation journals and periodicals.

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As can be inferred from the opinions expressed in current literature, the scientific community is concerned lest the adverse experience of other environmental problems be repeated. The most dangerous seems to be the steady increase of the number of space debris generated in the course of normal space activities and, in particular, the intentional as well as unintentional explosion and break-up of space objects. A collision with space debris could cause severe damage to an active satellite, in particular, manned missions.

The danger of space objects impacting on the ground as well as the pollution of the atmosphere by exhausts of launching rockets or by scientific release experiments seems to be at present within acceptable limits.

3 Space Debris

3.1 Terminology

The 1967 Outer Space Treaty and the 1976 Registration Convention use the terms "space objects" or "objects launched into outer space". These terms refer to artificial, man-made objects, not to natural ones, known in astronomy as "meteoroids". The extent of the term "space object" is not interpreted in quite the same way by State Parties to the above instruments. Within the framework of the Registration Convention, some States announce only the launchings of payloads while other States announce also launchings of non-functional objects, such as spent boosters, spent maneuvering stages, shrouds etc. For the purpose of this study, the term "space object" will be used for all objects launched into outer space, functional as well as non-functional, including debris.

"Debris" is a descriptive term of the same meaning as "fragment" or "fragments". There is no sharp limit between "debris" and "non-functional objects", the latter creating the impression of large objects while "debris" may refer also to small objects down to a fraction of a millimetre. Dust particles, molecules and gaseous components, dealt with in Sections 4 and 5, are not, as a rule, referred to a "debris".

An "active satellite" or "payload" is understood to be performing some intended function. After the termination of its activity, while still in orbit, it continues to be referred to as "payload" but it becomes an "inactive satellite". In the terminology of the International Telecommunication Union, an "active satellite" is defined, more narrowly, as an earth satellite carrying a station (i.e. radio transmitters and receivers) intended to transmit or retransmit radiocommunication signals [16].

The NASA Satellite Situation Report [17] uses two terms, "payload" and "debris" to cover all kinds of artificial space objects.

3.2 Trackable space objects

One of the sources of information on space objects is the NASA Satellite Situation Report [17]. It is based on data from the tracking network of the North American Aerospace Defense Command. The sensitivity of radars participating in that network permits the detection of objects of 4 cm diameter at 200-300 km altitude, or 10 cm diameter at 1000 km, or 1 m at

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5000 km altitude. Optical methods used for tracking space objects at higher altitudes permit the detection of 15 cm objects at 5000 km and 1 m objects at the geostationary orbit at a distance of almost 36000 km [18]. Only objects which have been observed by more than one radar and which could have been associated with a specific launch are included in the Report.

Diagrams of satellite populations near the Earth and as far as the geostationary orbit are shown in Figure 1 and 2. They refer to the situation on 1 January 1987 when the total number of trackable space objects was 6237. The latest available issue of the Satellite Situation Report of 30 June 1988 lists a total of 7184 space objects including 1777 payloads and 5407 debris in orbit around the Earth.

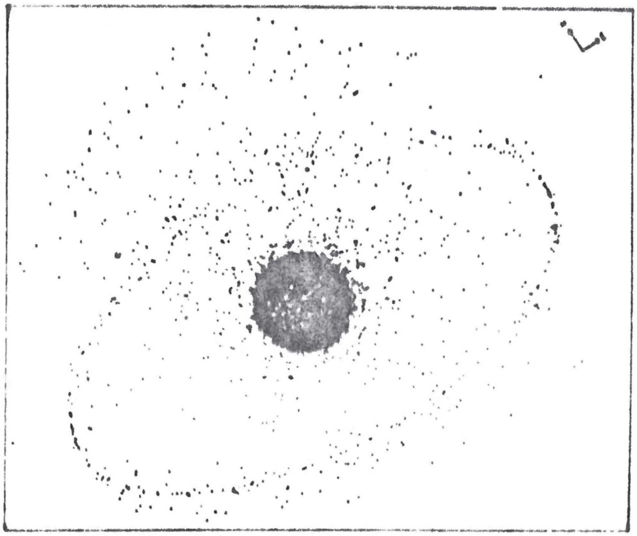

Figure 2: The same as Figure 1, in a scale showing the population by trackable space objects of the geostationary orbit and of highly eccentric orbits. Published in [1].

It was estimated [18, 26] that of the total population of trackable space objects in orbit are:

- 2-5% operational payloads,
- 21% non-operational payloads
- 25% mission-related debris, and
- 49% debris from satellite break-ups.

In other words, out of the over 7000 space objects, only 150 to 350 are active satellites while the rest do not perform any useful function.

Numbers of trackable space objects have been increasing since the beginning of the space era with the exception of a short period around 1979-1981, as shown in Figure 3. In that time-span, the number of launches as well as of payloads launched was below normal (see Fig. 4)

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and there were no break-ups of satellites producing large numbers of space debris. The most important effect, however, seems to be the maximum of solar activity of 1979–1980 [19]. One of the consequences of high solar activity is an increase in the density of the upper atmosphere. Specifically, the factor of increase is approximately:

4 times at an altitude of 300 km,
20 times at an altitude of 500 km, and
10 times at an altitude of 800 km.

The corresponding larger atmospheric drag makes the lifetimes of satellites shorter and they decay sooner. After the solar maximum, there remained less debris in orbit at altitudes of 300–800 km and outer space was partly cleaned up. About 30% of trackable space objects decayed prematurely thanks to the 1979–1980 solar maximum.

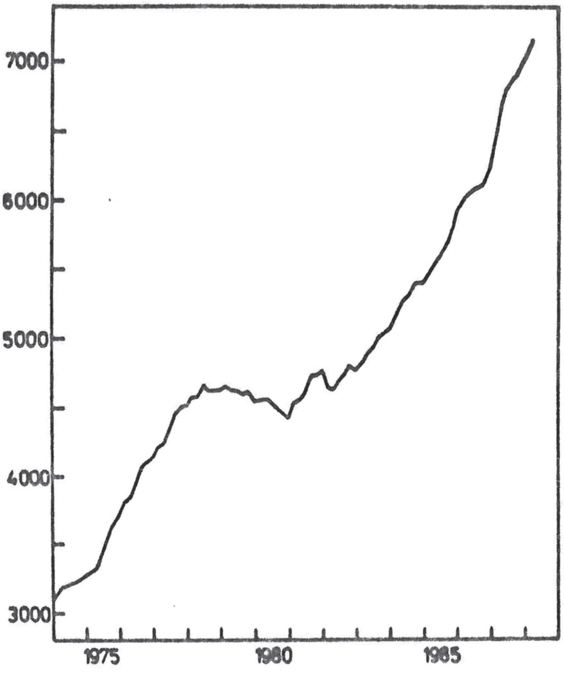

Figure 3: Numbers of trackable space objects in earth orbit.

After the maximum, between 1983–1988, the increase of numbers of space objects has been fast, possibly faster then before the maximum. Since the number of launches and of payloads has not been increasing, as shown in Figure 4, we have to conclude that technology and design of satellites have not yet contributed to a limitation in numbers of debris.

Trackable space objects appear with highest frequency at altitudes between 800–1000 km and around 1500 km. This is shown in Figure 5 which gives spatial densities of space objects in

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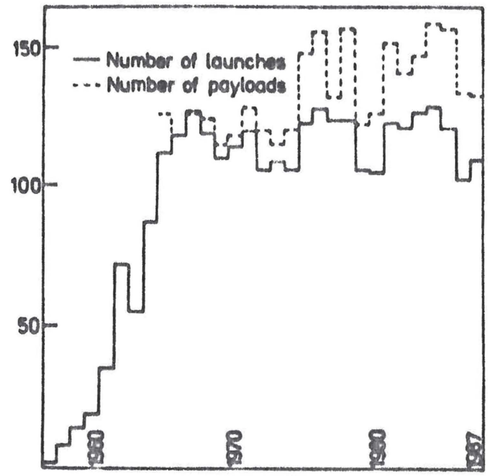

Figure 4: Numbers of launches and payloads per year.

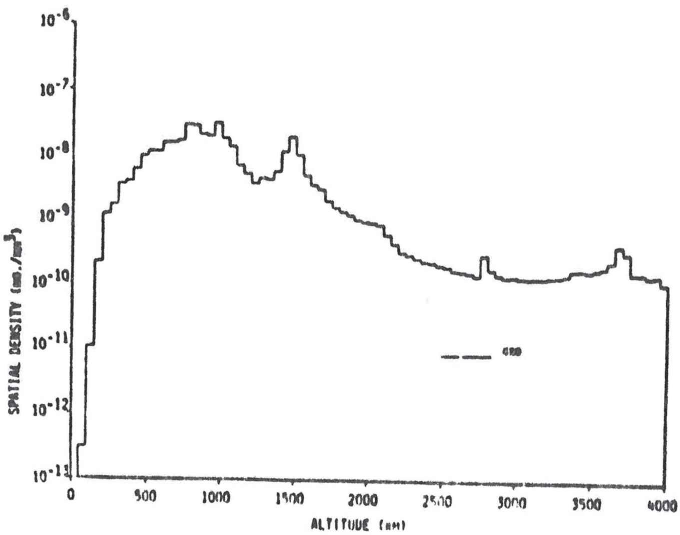

Figure 5: Spatial density of trackable space objects, as of 31 March 1988, plotted against altitudes.

numbers of objects per cubic kilometer. The diagram corresponds to the state as of 31 March 1988 and was taken from [15].

3.3 Non-trackable debris

Objects which are too small to be detected by current means certainly exist in numbers exceeding several times the numbers of trackable debris. Some authors, rather conservatively, estimated the amount of non-trackable debris to 2-4 times the number of trackable objects. An experiment, conducted at the Lincoln Laboratory of the Massachusetts Institute of Technology [20] showed, during a limited period of time, that debris down to 1 cm size are 8 times as populous in low earth orbits as tracked space objects. There were indications that even as far as the geostationary orbit there are substantial numbers of debris escaping detection by conventional instrumentation.

On the other hand, during a search for geosynchronous debris by T.Gehrels and F. Vilas [21] only 10 objects were recorded, most of them satellites, but some showing north-south motions indicative of inactive objects. Although fainter geostationary debris could have been identified if present, no objects were found smaller than about 2.5 m diameter. The search was made on 5 nights in 1984 and covered 16.4 square degrees, a very small part of the geostationary belt.

One of the few cases when the impact of a non-trackable debris was indeed observed is the case of Space Shuttle flight STS-7 [13, 22]. While in orbit, the crew detected a pit on the outside window of 5 mm diameter. An examination after landing has shown that the pit contained titanium with a trace of aluminum. The particle had a diameter of 0.2 mm and an impact velocity of 3-6 km/s. It was a flake of paint from another space object.

The results of considerably more extensive efforts will have to be awaited before good data can be substituted for present estimates of the numbers and size distribution of small debris. Only then it will be possible to determine reliably the degree of pollution of outer space by artificial solid objects.

3.4 Origin of debris

Some debris is related to the normal function of the launching vehicle and spacecraft. These are the rejected shrouds, spent rocket stages, covers, explosive bolts used in separation of stages and flakes of paint peeled off from orbiting space objects. These are called mission-related debris.

By far the most prolific source of space debris are explosions and break-ups. The first break-up of a satellite occurred in 1961. An Ablestar rocket exploded due to an unknown cause and generated over 280 trackable pieces of debris. Over 80 explosions and break-ups have been recorded since that time [14] as shown in Table 1. The data refer to the end of 1986 and have been updated to the end of 1987 in the bottom part of the table on the basis of data in the Satellite Situation Report [17].

The numbers in Table 1 are not final because debris continues to be detected. E.g., the Ariane V 16 rocket which exploded in November 1986, figures in the 1986 data with 80 debris pieces known at that time. In the course of 1987, 370 additional debris were discovered and 20 more in the first half of 1988. One satellite broke up in 1987 and two more 1987 launches generated 38 and 66 pieces of debris respectively in 1988.

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Table 1:

Cause of break-up	Deliberate	Propulsion-related	Unknown	Total
As of 31 December 1986:				
Number of break-ups	34	13	39	86
Number of fragments				
- catalogued	2094	1791	2078	5963
- in orbit	737	945	1141	2823
As of 31 December 1987:				
Number of break-ups	35	13	39	87
Number of fragments				
- catalogued	2421	1848	2639	6908
- in orbit	1130	867	1663	3660

Many explosions or break-ups have to be listed under unknown causes because of scarcity of observations and the inherent difficulty in reconstructing an event which happened far out in outer space. One example when the cause of a break-up was identified is the case of the Delta second stage. It appears that in a specific orbit, solar heating causes the degradation of the common bulkhead between the fuel and the oxidizer. The remnants of the two chemicals explode on contact. When the cause was recognized, depletion burns were installed [14] and since that time no Delta rocket exploded.

Table 2, taken from [9], lists the ten break-ups and explosions which produced the largest numbers of debris. It gives the data as of 1987. Objects larger than 10 cm have been detected by tracking while the numbers of objects larger than 1 mm are estimates.

3.5 Impact of debris: decay and fall

Due to the braking effect of atmospheric gases, space objects spiral down into the denser layers of the atmosphere where the drag is more powerful and the spiralling accelerated. This is illustrated in Table 3, based on data in [23]:

For time spans shorter than the period of solar activity (11 years) the times may vary according to the actual degree of solar activity. E.g., the Skylab 1 rocket, 197-027B, which was observed many times before its decay on 11 January 1975 [24], i.e., at a time of a minimum of solar activity, needed for its descent the times shown in the bottom part of Table 3. It should be noted that Table 3 refers to satellites of an average design. Heavy and compact satellites descend more slowly, whereas very light objects, such as inflated balloons, descend more rapidly.

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Table 2: The ten worst upper stage and satellite break-ups as of 1987

Date	Objects	Break-up altitude km	Number of objects			
			Larger than 10 cm		Larger than 1 cm	
			initially	in orbit	initially	in orbit
15.10.65	Titan 3C-4	739	467	88	1990	308
13.11.86	Ariane 3rd stage	820	465	462	2330	2104
17.10.70	Thor-Agena-D	1076	346	294	1872	1538
24.07.81	Cosmos 1275	977	281	276	1250	1041
29.06.61	Ablestar rocket	950	271	209	1716	899
04.10.69	Thor-Agena-D	919	264	140	1112	734
13.09.85	Solwind	530	251	194	-	-
25.07.76	Cosmos 844	209	248	0	476	0
22.05.75	Delta 2nd stage	725	227	94	1520	381
19.06.76	Delta 2nd stage	751	201	55	1120	375

Table 3:

To descend from an altitude of	to altitude of	a satellite in a circular orbits takes
1000 km	900 km	1200 years
900 km	800 km	540 years
800 km	700 km	270 years
700 km	600 km	85 years
600 km	500 km	14 years
500 km	400 km	9 years
400 km	300 km	516 days
300 km	200 km	54 days
200 km	0 km	4 days

When a space object in a circular orbit gets down to about 150 km altitude, it heats up by friction with the atmosphere and eventually most of its mass evaporates. Only compact parts may survive this phase and impact on the ground or into the ocean. The process is considerably more complicated for highly elliptical orbits. Their perigees are loosing altitude only slowly and may even dip into altitudes which are fatal for circular orbits, to be lifted by lunisolar perturbations and preserved in orbit for several more years. E.g., Molniya 2B, 1972-037A, had its perigee as low as 113 km in November 1973, but contrary to expectation did not decay. The perigee altitude then increased and reached 420 km in September 1975. After a new decline of the perigee altitude, the decay came in March 1977 [23], as shown in Figure 6.

The number of decaying objects is fairly large, about 500 per year. Most of the decaying objects, however, either evaporate in the atmosphere or their impact on the ground goes unnoticed. Although States are obliged to announce to the United Nations space objects or their

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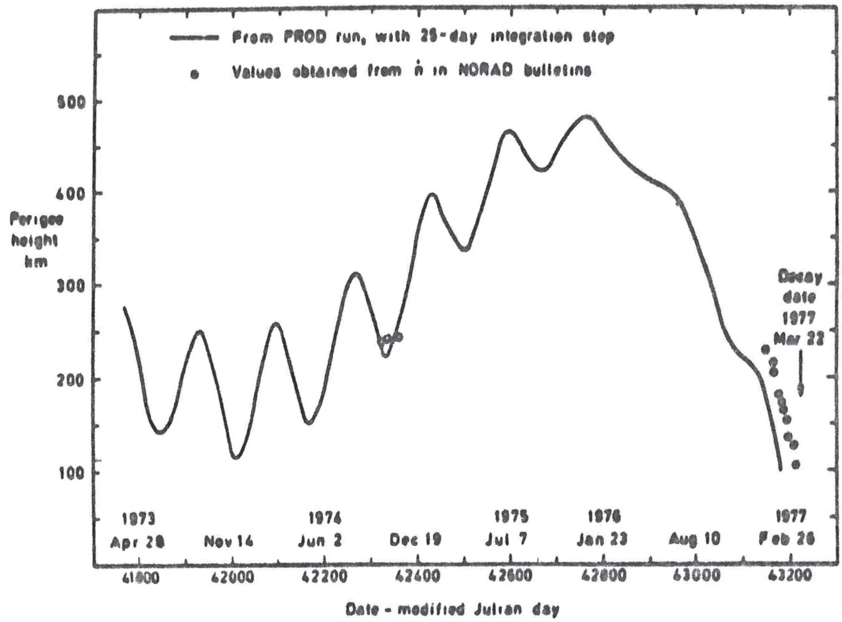

Figure 6: Perigee altitudes of Molniya 2B plotted against dates.

parts found on their territories with a view to return them to the launching state[1], in the course of 18 years, from 1968–1985, only 17 announcements have been received by the United Nations.

Among the objects whose fall received wide publicity was Cosmos 954 which had a nuclear power source on board and disrupted over northern Canada[2]. Another rather famous case was the fall of Skylab 1, 1973-027A, an object of 75 tons which disintegrated on 11 July 1979 over south-west Australia. Still another case with a nuclear power source on board were two fragments of Cosmos 1402, 1982-084A and C.

It is very difficult to predict the time and place of a decaying object with sufficient accuracy. The most critical factor is the solar activity (see Section 3.2) which cannot be predicted reliably. In addition, the atmospheric drag depends not only on the density of the atmosphere but also on the shape and compactness of the space object. Both may change in the last phases of orbital life because of thermal effects and possible losses of protruding parts such as antennas or solar panels. Important is also the attitude or tumbling motion of the object. Most specialists agree that predictions made under favourable conditions are accurate to about 10% of remaining

[1] According to the Agreement on the Rescue of Astronauts, the return of astronauts and the return of objects launched into outer space.

[2] The item "Use of nuclear power sources in outer space" including their debris, is on the agenda of the Committee on the Peaceful Uses of Outer Space and of both its Sub Committees. Consequently, its subject matter has not been elaborated in this study.

lifetime. Thus the prediction of the last orbit, or 40000 km on the ground, cannot be made sooner than 15 hours before impact, and only in the last 22 minutes can the impact point be predicted within a strip 1000 km long. At a time when the continent or country of impact becomes known with some degree of certainty, there is hardly any time left to publish and disseminate a meaningful announcement.

3.6 Impact of debris: collisions

A collision of objects in outer space used to be considered highly unlikely, if not impossible, because of the enormous expanse of space and the relatively small number of space objects. But space activities are entering now their fourth decade and numbers of space objects are increasing fast. Consequently, the danger of collisions between space objects has to be evaluated.

Several authors have determined collision probabilities in space. In the first approximation the problem can be solved by methods developed in the kinetic theory of gases for collisions of molecules. The collision probability is proportional to the relative velocity of the two objects, to their sizes and, what is most important, to the number of objects per unit volume of space, i.e. to the density of space objects. The relevant formula contains the square of the density. Thus an increase in the number of space debris by 5% raises the collision probability by 10% and an increase by 40% doubles the collision probability.

Table 4 gives values for the altitude range 300-700 km which is important for manned space missions, although the highest collision probabilities occur higher, between 800-1000 km. Instead of probabilities, the Table gives a more illustrative parameter, the average time between collisions. It is based, for the year 1984 and for trackable debris, on a diagram reproduced in [14]. Other data are easily deduced. The first line for each year refers to trackable debris only. These are the values which can be determined from observations. It is, however, the second line for each year that gives a realistic picture of the collision danger because it refers also to an estimated number of non-trackable objects. Actual numbers of trackable space objects are given for 1984 and 1988. It was assumed that their increase until 2000 will not be faster than at present.

Table 4:

Year	Number of debris		Average time between collisions	
	Trackable	Non-trackable	Space Shuttle	Space Station diameter 100 m
1984	5000	0	3000 - 30000 years	100 - 1000 years
	5000	40000	50 - 500 years	2 - 15 years
1988	7000	0	1500 - 15000 years	50 - 500 years
	7000	56000	25 - 250 years	1 - 8 years
2000	10000	0	750 - 7500 years	25 - 250 years
	10000	80000	12 - 125 years	0.5 - 4 years

Table 4 shows clearly the dependence of collision probabilities on the number of debris and on the size of the target. Evidently, collision danger is increasing and will increase in the future even if the level of space activities remains approximately the same.

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In reality, collision probabilities may be considerably larger and the times between collisions shorter than those shown in Table 4. The reason is that space objects do not move quite as randomly as molecules in a gas do but are subject to systematic and periodic motions following from laws of celestial mechanics. A cloud of debris gererated by an explosion expands, assumes an ellipsoidal shape, later forms a torus around the Earth and finally disperses into the general background of debris. The orbits of individual pieces are shown in Figure 7 for 100 largest fragments of the Ariane V 16 explosion [9]. The density in the cloud is very high immediately after explosion. The expansion of the cloud is not uniform. Twice during each revolution the cloud contracts into a small area (see Fig. 7, top right), a "pinch point" of a high spatial density. The collision probability in the vicinity of the pinch points is much higher than its average value [25]. The satellite SPOT 1, 1986-019A, placed into orbit by Ariane V 16, is close to the orbit of the cloud. A. Ducrocq [26] estimated that SPOT 1 had a change of 7 in 10 in surviving until autumn 1987, which it did, and a chance of 1 in 2 to survive until 1989. Both chances are well below the average.

Another point to keep in mind when examining Table 4 is that the number of debris is increasing at all times because new debris is generated in any collision of two objects. According to Kessler [18] a typical collision between an old rocket body or payload and a small fragment larger than 4 cm could produce 10000 particles larger than 1 cm and over 1 million particles larger than 1 mm. Consequently, collision probabilities will increase in the future even if not a single space object is launched any more.

The average velocity between a piece of debris and the target is of the order of 10 km/s. At this speed, the impact of even a very small object may cause considerable damage to an active satellite. Computations and experiments show [27] that the small impacting object will melt or evaporate and form a number of small high velocity fragments. The large object will develop a crater or a hole and may break up even outside the area of impact. The mass ejected from the large object will be more than 100 times larger than the mass of the small object. A metallic sphere of 1 cm diameter and mass of 4 g will eject from a satellite over 400 g of material. Such an impact could be fatal for any satellite.

Some collisions may have already happened. Among the candidates is GEOS 2, 1978-071A, which developed a fault [28] three days after it became fully operational. The supply of electric energy became irregular. It was attributed to a mechanical damage suffered by a section of a solar array panel. Another case was Cosmos 954, 1977-090A, which lost pressurization on 6 January 1978, started to tumble and rapidly decayed. The opinion was expressed by L. Sedov [29] that the satellite collided in flight with some other object of natural or artificial origin. The best candidate for a collision is Cosmos 1275, 1981-053A, which broke up seven weeks after launch at an altitude close to 1000 km. D.S. McKnight [30] presented several indications that the break-up was the consequence of a hypervelocity collision. The break-up of Pageos, 1966-056A, which was in an almost polar orbit at an average altitude of 4200 km, belongs also on this list. It generated fragments on two occasions without a plausible explanation ever having been proposed.

A very special case is the geostationary orbit. As was shown in Section 3.3, our knowledge of the numbers of debris below 1 m is inconclusive. If collision probabilities are computed from the numbers of trackable objects, the average time between collisions is of the order of 500 years [31, 32]. This is an average value and the danger of collision may be much higher in crowded parts of the orbit. The collision danger with its possible damage to an expensive active satellite is being taken seriously by agencies operating geostationary satellites. On some

3 *SPACE DEBRIS*

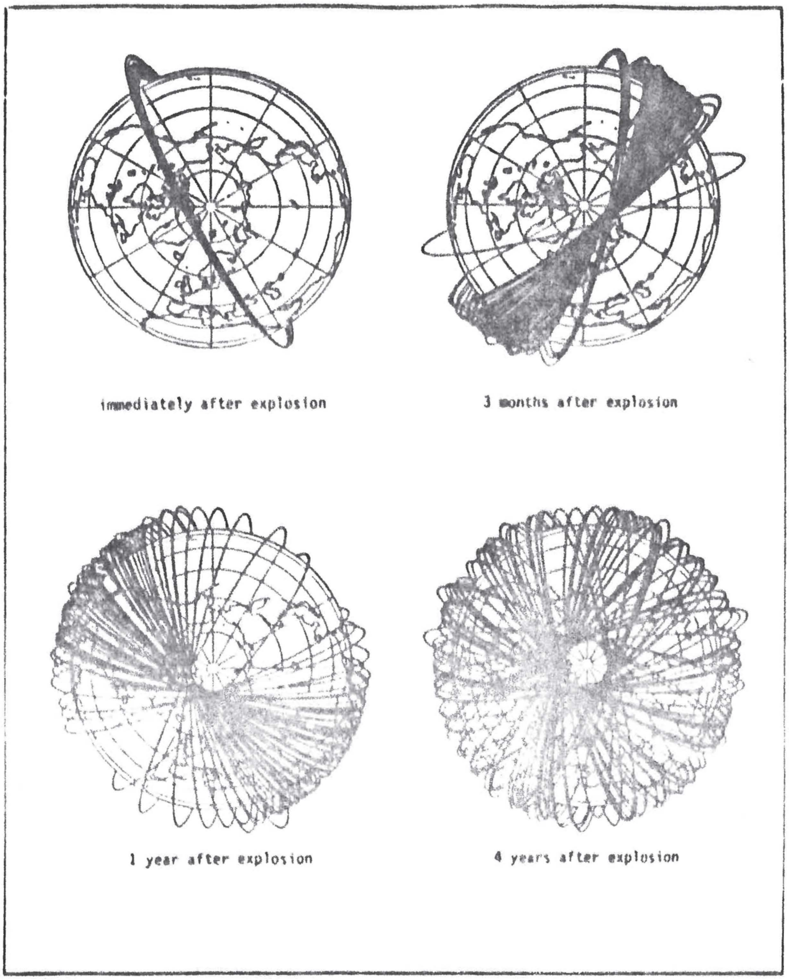

***Figure 7:** Evolution of the spatial distribution of explosion fragments. Computer simulation of 100 largest fragments of Ariane V16 explosion [9]*

3 SPACE DEBRIS

occasions evasive maneuvers have been performed to prevent close encounters or collision [33]. Relative velocities between objects in the geostationary orbit are much smaller than in low earth orbits. Nevertheless, they are between 500–1000 km/h, more than enough for destruction or severe damage.

The risk of collision with active spacecraft in the geostationary orbit and blockage of beams of operational satellites due to the presence of uncontrolled man-made objects was discussed at the WARC-ORB 1985 [34]. The Conference resolved to urge the CCIR (Comite Consultatif International de Radiocommunications) to develop for the second session of the Conference, to be held in 1988, a better understanding of this interference, in particular, to identify relevant factors, to evaluate future risks and to recommend a solution of the problem should the study results justify further action.

3.7 Possible preventive measures

Little can be done about inactive objects and debris which are already in orbit. Man-made cleaning actions are beyond the capabilities of present technology. The only natural cleaning effect, the atmospheric drag enhanced by solar activity, cannot cope with all debris generated in the course of space operations and is inefficient at altitudes above a few hundred kilometers. Many scientists (see individual papers in [4], [6], [7]) have proposed preventive measures and some of these have been adopted by some launching States or agencies. There is, however, neither an international agreement, nor universal application, nor recommendation of such measures.

An improved design of rockets and satellites could result in generating smaller numbers of mission-related debris during the launching and operation phases. In particular, the avoidance of intentional, and prevention of accidental explosions would cut the number of debris in half.

A systematic planning and speeding up of the decay of non-functional objects and of payloads after the termination of their active functions, if universally applied, would remove some 20% of inactive space objects. The decay could be speeded up by drag augmentation, e.g., through the use of balloons that would inflate at the end of active life, or, above 700 km altitude, by lowering the perigee through a propulsion burn [35].

At high orbits, where an intended decay into the dense layers of the atmosphere would require prohibitive amounts of fuel, inactive satellites can be removed into disposal orbits at altitudes not used for active missions. This solution has been effectively used for several satellites in the geostationary orbit. Such removals were first performed by Intelsat in 1977 and later by other launching States and agencies.

Another international provision or recommendation has been advocated frequently: Outer space should be used for useful missions in the spirit of the Outer Space Treaty, not for useless missions, e.g. those commemorating an event or an achievement. Monuments, according to the advocates of this provision, should be built on Earth, not in space where they could become threats to future peaceful space operations.

Still another idea calls for a partial traffic separation by reserving certain internationally agreed lanes or altitudes for specific peaceful applications and for active satellites.

Some scientists point out the fact that publicly available information on space objects, although very valuable, permits to compute for each space object only the general area where it moves, not its instantaneous position. The latter is quite important, e.g., for avoiding close encounters or collisions during the launching phases of manned and other sensitive missions. Thus a more comprehensive and timely flow of information on orbital and other data of all trackable space objects is advocated.

4 Dust in Near Earth Space

In addition to man-made debris in space there is also an extraterrestrial particle population, the meteoroids, whose origin include comets, asteroids, the moon, and possibly an interstellar component acquired when our solar system in its revolution around the galactic center sweeps through the interstellar medium.

Extraterrestrial "debris" (meteoroids) ranges in size from macromolecules to kilometer objects, with masses from 10^{-17}g to 10^{16}g; the larger ones however, being extremely rare. The mass density of small extraterrestrial "debris" is typically between 0.5-2g/cm^3, significantly lower than man-made debris.

Because of their complex orbits meteoroids are encountering earth orbiting objects from random directions with velocities in the range from 12 to 72 km/s, meteoroids originating in comets stay in the vicinity of their parent bodies, producing the well known meteor-showers when the earth crosses their orbital plane. The total influx of extraterrestrial dust particles on the earth is estimated to be about 4000 tons per year.

The cumulative flux of cosmic particles (micrometeoroids) in near earth space is already quite well known from a number in situ experiments on spacecraft, including Skylab, the Space Shuttle as well as from recovered parts of the Solar Max satellite. Based on these data the cumulative flux on a "spinning plate" near earth has been calculated [36]; the mass distribution of these particles has a maximum in the microgram range (10^{-6}). The flux of extraterrestrial particles and man made space debris encountered by a spacecraft in low earth orbit (LEO) as well as the expected impact crater size is shown in Fig. 8. An impact velocity of 8 km/s is representative for man made debris, 20 km/s for extraterrestrial particles. It is quite obvious that in the picogram (10^{-9}g) mass range man-made debris predominates, whereas in the microgram (10^{-6}g) range both fluxes are comparable. However, for much larger masses and sizes man-made debris fluxes predominate over natural particle fluxes. This is also apparent from Fig. 9 which shows the expected impacts per year for a cross sectional area of 1 m^2; for particle sizes greater than 1 mm man-made debris becomes the dominant cause of impacts [37].

5 Chemical Pollution by Space Activities

5.1 Introduction

Since the beginning of the space age, the scientific community, through the International Council of Scientific Unions (ICSU) has voiced concern that large rockets used for the launching of satellites and space probes would introduce into the atmosphere and near-earth space matter that could possibly have adverse affects not only on scientific observations, but may also change the natural state of our environment. Twenty five years ago COSPAR commissioned the first

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4 DUST IN NEAR EARTH SPACE

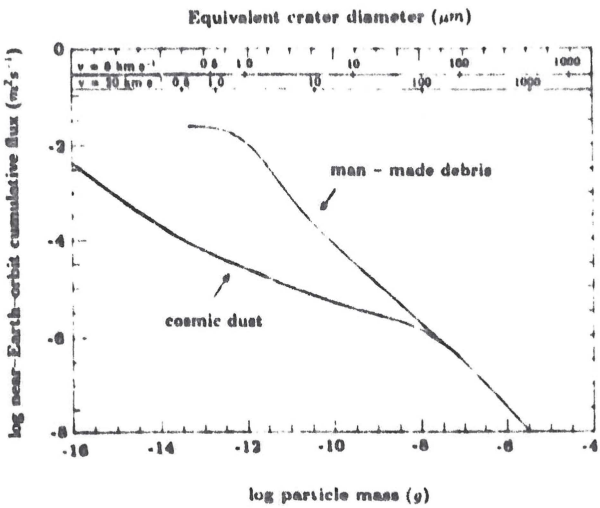

Figure 8: Flux of extraterrestrial and spacecraft debris particles in low Earth orbit.

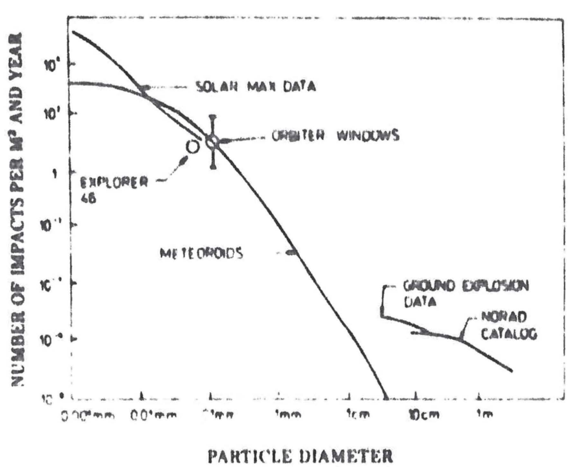

Figure 9 Number of impacts per m^2 and year of extraterrestrial particles and man made debris as function of their diameter

study devoted to an assessment of potential pollution of the upper atmosphere by rockets [38]. The conclusion of this study was, that (a never realized) launch rate of 10^3 to 10^5 Saturn type rockets (then the largest launch vehicle) per year would be required to drastically change the atmospheric content of important constituents such as CO_2, H_2O and NO and that chemical release experiments would be capable of changing significantly the content of such trace elements as sodium (Na) and Lithium (Li).

Four years ago a new assessment study of chemical pollution by space activities was performed for COPUOS by COSPAR [39]; the present section represents a summary and update of its conclusions.

In evaluating the possible effect of chemical pollution of the atmosphere by space activities, comparisons of injected masses to those present in the natural environment must be made. We therefore shall discuss briefly the pertinent properties of the natural environment.

5.2 Earth's atmosphere

The atmosphere is generally divided into different regions on the basis of its temperature structure (Fig. 10).

The lowermost part where the temperature decreases with height due to large- scale convection of air resulting from our weather processes is called the *troposphere*. Above its boundary, the tropopause, the temperature increases again due to the absorption of solar ultraviolet radiation by the trace constituent ozone (O_3) which also protects life on Earth from this harmful radiation. This region is called the *stratosphere*. Above the stratopause, there is a region of decreasing temperature, the *mesosphere*, beyond which the gas temperature rises again as the result of atmospheric absorption of the shortest wavelength (extreme ultraviolet) solar radiation. This region is called the *thermosphere* for the neutral gas, but since here the atmosphere becomes increasingly ionized (consisting of electrically charged particles, i.e. electrons and ions), this region is also known as the *ionosphere*. The "sphere of influence" of the Earth's magnetic field, on charged particles, extending far beyond the ionosphere, is known as the *magnetosphere*.

Up to about 100 km in altitude, the atmosphere is thoroughly mixed (*homosphere*), above the homopause, in the *heterosphere* the lighter gases begin to dominate over the heavier ones so that the atmospheric composition changes from molecular to atmospheric species (O,He, H). Table 5 shows the atmospheric composition in the mixed regions (homosphere).

The atmosphere is in hydrostatic equilibrium, i.e., the atmospheric pressure and density decrease exponentially with altitude in such a way that, at least in the lower atmosphere, the pressure decreases every 10 km to about one third. of its preceding value. At greater altitudes, in the ionosphere, the atmosphere is already very tenuous so that atmospheric particles may travel many kilometers before encountering a collision with a partner (i.e., the mean free path becomes very large).

The total mass of the atmosphere which depends on the surface pressure, the acceleration of gravity and the surface area of the Earth amounts to 5×10^{15} tons. Because of the exponentially decreasing pressure, more than 90% of this mass resides in the troposphere, and less than 1% above the stratosphere.

5 CHEMICAL POLLUTION BY SPACE ACTIVITIES

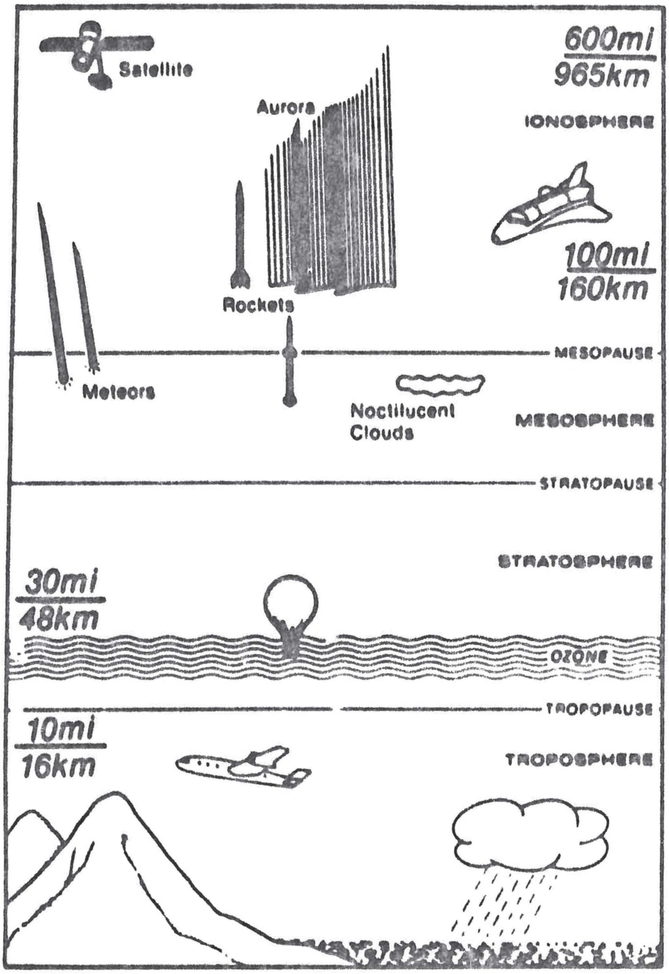

Figure 10: Regions of the Earth's atmosphere.

5 CHEMICAL POLLUTION BY SPACE ACTIVITIES

Table 5: Atmospheric Composition

Main constituents[3]	
	Molar (or volume) fraction
N_2	0.7809
O_2	0.2095
Ar	0.0093
CO_2	0.00034

Minor Constituents			
Non variable	Concentration[4]	Variable	Typical Concentration[5]
Ne	18 ppm (in volume)	O_3	Up to 10 ppm in stratosphere
He	5 ppm		5–50 ppb (unpolluted air)
Kr	1 ppm		Up to 500ppb in polluted air at ground
Xe	0.09 ppm	H_2S	0.2 ppb (over land)
CH_4	1.5 ppm	SO_2	0.2 ppb (over land)
CO	0.1 ppm	NH_3	6 ppb (over land)
H_2	0.5 ppm	NO_2	1 ppb (over land)
N_2O	0.25 ppm		100 ppb in polluted air
		CH_2O	0–10 ppb

5.3 Chemical effluents by rocket engines

A rocket engine injects exhaust material into the atmosphere throughout its burn. We shall now consider the effects of adding such exhaust materials to the atmosphere as a whole. Gaseous pollutants usually become thoroughly mixed with the ambient medium; aerosols (particulates) have a relative short lifetime in the troposphere but can persist for several years in the upper regions. Of particular interest is the addition of those trace constituents that play a major role in the atmosphere and biosphere [40].

Because of the ready availability of data on the exhaust products of the U.S. Space Shuttle [41], we shall consider this launch system as representative of large boosters. For our discussion, the effects of pollution by large rockets shall therefore be treated in terms of "Shuttle equivalents". (The newly developed *Energia* launch vehicle of the USSR may exceed the propellant power of the shuttle, but others like the *Proton* boosters lie below.) During its ascent through the atmosphere the Shuttle burns about 10^6 kg of solid propellant in two boosters and approx. 7×10^5kg hydrogen/oxygen in the main engine. The largest amount of matter released *in orbit* consists of 142 kg water per day produced by the fuel cell system. A detailed breakdown of released material in specific altitude regions is given in Table 6.

One of the major exhaust products is CO_2 that is also present in the atmosphere as trace

[3] H_2O is a variable constituent of $\lesssim 0.01$.
[4] ppm $= 10^{-6}$
[5] ppb $= 10^{-9}$

5 CHEMICAL POLLUTION BY SPACE ACTIVITIES

Table 6: Exhaust Effluents of the Space Shuttle

Atmospheric Layer	Altitude Range	Combustion Product	Single Mission Quantity Emitted (Kilograms) Solid Rocket Motors	Orbiter
Surface Boundary Layer	0–500 m	CO	37 200	
		CO_2	6 600	
		HCl	31 900	
		Cl_2	91.6	
		Al_2O_3	43 300	
		H_2O	15 870	19 520
Troposphere	0.5–10 km	CO	113 100	
		CO_2	20 100	
		HCl	96 900	
		Cl_2	278	
		Al_2O_3	131 600	
		H_2O	48 200	62 200
Stratosphere	10–50 km	CO	115 100	
		CO_2	20 440	
		HCl	98 800	
		Cl_2	284	
		Al_2O_3	134 100	
		H_2O	49 900	115 000
Lower Mesosphere	50–67 km	CO	0	
		CO_2	0	
		HCl	0	
		Cl_2	0	
		Al_2O_3	0	
		H_2O	0	49 000
Mesosphere Thermosphere above	67 km – ∞	H_2O	0	402 500

constituent with an abundance of 340 ppm (see Table 5). CO_2 is of special importance to the world's climate, since it plays a major role in the "greenhouse effect", i.e., it is transparent to visible solar radiation, while blocking outgoing terrestrial infrared radiation, thus increasing the earth's surface temperature.

It is now recognized that the CO_2 content of our atmosphere has been increasing over the past century, primarily due to the burning of fossil fuels. The amount of CO_2 released from fossil fuel burning between 1959 and 1980 has been estimated to be about 8×10^{13}kg, which corresponds to 4×10^{12}kg/year on average in this period. A doubling of the present CO_2 content of the atmosphere is considered to result in an increase of the globally averaged surface temperature by 2 to 3°K. With continuing yearly release rates of the above magnitude, such a doubling is expected to occur in the next century.

Let us now estimate the contribution of large scale launch activities to the increase of atmospheric CO_2. A single "Shuttle launch" produces at most 3×10^5 kg of CO_2 (all sources considered). Assuming a launch rate of 100/year or two launches per week, in a most optimistic scenario involving the development of the U.S. Space Station as well as frequent large launches by the USSR, the yearly injection rate of CO_2 due to launch activities is about 3×10^7kg or 10^{-5} of the yearly injection rate from fossil fuel burning. The present mass of CO_2 in the atmosphere is about 3×10^{15}kg. (Although the present worldwide launch rate amounts to about 100 launches per year, most of them employ rockets with less propellant power and exhaust products than the Shuttle scenario considered above.)

Another exhaust effluent that may be of some concern in terms of environmental effects is hydrochloric acid (HCl) which, injected into the stratosphere, may provide free chlorine (Cl) that has been identified, together with nitric oxide (NO) as a major catalytic reactant in the removal of ozone (O_3).

The major stratospheric source of chlorine is the dissociation of chlorofluorocarbons (CFC) such as $CFCl_3$ (F-11) and CF_2Cl_2 (F-12) released into the atmosphere by man. Over the last 10 years, about 8×10^8kg of F-11 and F-12 were produced world-wide per year which were, or potentially will be, released into the atmosphere. (They are now also implicated as a contributing cause of the seasonal antarctic ozone hole.) Comparing this amount with the release of 10^7kg HCl/year from 100 "Shuttle launches", it is obvious that even for such a scenario, launch activities would provide only about 1% of the total anthropogenic input of chlorine into the stratosphere. (HCl as such does not interact with O_3 but is a "reservoir" of Cl).

The second catalytic reactant in the ozone removal process, nitric oxide, is produced in the shock-heated entry wake of the Shuttle where atmospheric nitrogen and oxygen are converted into NO. Even for 100 launches and entries a year, the production rate of NO is only about 10^{-3} that of the natural production rate.

From the foregoing discussion it is obvious, that the atmospheric injection rates of environmentally important trace constituents for even "100 Shuttle - equivalent launches" per year are negligibly small compared to natural or other anthropogenic sources.

Release of water in the ionosphere can cause a temporary and local depletion of ionization by a factor of 2, a so-called ionospheric hole, because of chemical reactions with the ambient ions. An extreme case of such an ionospheric hole, covering an area of 1 million km^2, was observed 15 years ago during the exceptional case of a Saturn V main-engine burning in the altitude range between 200 - 400 km. Launch systems with hydrogen/oxygen boosters (e.g., the Energia) producing as their main exhaust products CO_2 and H_2O in the stratosphere and H_2O and H_2 in the mesosphere can also produce noctilucent clouds (see Fig. 11) lasting for several hours, an otherwise natural phenomenon having no environmental impact. Recently, however, concern has been voiced that ice crystals in these clouds may affect re-entry procedures of the Shuttle.

5.4 Chemical gas releases for scientific purposes

Chemical releases, particularly of sodium (Na), barium (Ba), strontium (Sr) and lithium (Li) have been made for the past two decades to study winds in the mesosphere and thermosphere and electric fields in the ionosphere and magnetosphere. Worldwide the total number of experimental gas releases has been less than 400, the total mass of the released material about five tons. Most of the individual releases have been in the mass range from 10 to 50 kg a few have exceeded

100 kg. Barium releases usually include 1 to 2% strontium, several include sodium or lithium doping while lithium trails sometimes as include sodium.

Large mass release experiments (>100 kg) can also be viewed as "active experiments in space" since the kinetic energy at orbital velocity 8 km/s for 100 kg of release material can be used for the modification and perturbation of natural systems as well as for large scale simulation experiments (e.g. "artificial comets ") as was done in the AMPTE program in 1984/1985 [42].

Past chemical releases in the altitude region from 150 to 900 km (within the ionosphere) with a total released mass of several tons have shown no adverse affects on the terrestrial environment. The maximum total mass injection by chemical release experiments, with the exception of barium and lithium, however, is only a minute fraction of the meteoritic mass influx.

No deleterious effects of chemical releases are anticipated that affect astronomical observations. All luminous experiments create glows which are transient in nature, lasting at most tens of minutes and in some cases up to an hour or two. In the worst case a chemical release would only interfere with astronomical observations if they were made in that particular area of the sky under clear-sky conditions. The presently projected chemical release experiments, even with injection rates of several tons per year, do not seem to cause any significant environmental effects.

5.5 Environmental consequences

In spite of many hundreds of rocket launches since the advent of the space age, no concrete evidence has been found to suggest that rocket effluents may be deleterious to our environment. The only observed effects were instances of local ionospheric depletions ("holes"), lasting for several hours, when rockets burned within the ionospheric F-region. Estimates of possible environmental consequences of a high global launch rate, exemplified by 100 Space Shuttle launches a year, or twice a week, also indicate an undetectable addition of exhaust products to our atmosphere. Even environmentally important trace constituents, such as CO_2 (responsible for the greenhouse effect) or chlorine (Cl) and nitric oxide (NO), involved in the catalytic destruction of ozone (O_3), would show increases completely negligible compared to natural or other anthropogenic sources: The addition of CO_2 from 100 Shuttle launches per year would amount to only 10^{-5} of the yearly injection rate from the burning of fossil fuels. The release of chlorine into the stratosphere from the hydrogen chloride (HCl) contained in the Shuttle propellant, amounts to less than 1% of the anthropogenic input from chlorofluorocarbons (CFC), while the generation of nitric oxide (NO) during re-entry amounts to about 0.1% of the natural production rate. Even if a highly optimistic threefold global launch rate is projected for the next century, environmental effects would still remain negligible compared to other anthropogenic causes.

Past and projected chemical releases for scientific purposes seem to pose no environmental problems at all.

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