Astronomical Light Pollution by Artificial Earth Satellites

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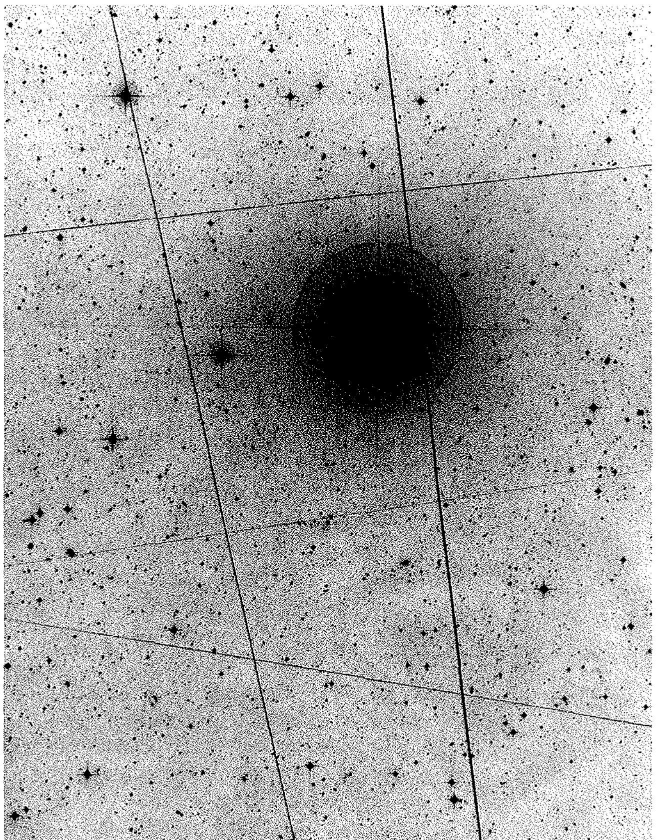
Since the launch of Sputnik 1 in 1957, the space programme has expanded to become an integral part of our lives in a multitude of ways. Many nations contribute, very many benefit and a growing number have the technological ability to launch spacecraft into Earth orbit. While we may appreciate many of the results, e.g., vastly improved communications, satellite TV, better weather forecasts, etc., and we certainly value the contribution to astronomy and science in general, there are a number of side-effects which cause considerable concern. The physical dangers to spacecraft inherent in the increasingly crowded near-earth environment have caused both NASA and ESA to examine the risks and propose tighter management of their missions to avoid further unnecessary litter (ESA set up a "Space Debris Working Group", chaired by Flury, 1988). There are particular dangers to manned missions in low-earth-orbit (LEO) and large structures like the space station "Freedom" risk a high probability of collision and damage. The Hubble Space Telescope risks a 50 % probability of collision with a particle smaller than 5 mm in its proposed 17-year lifetime (Shara and Johnston, 1986). The Geostationary orbit is, understandably, crowded and measures are now usually taken to remove expiring satellites and place them in safe "parking orbits", freeing space for replacements.

Ethical issues are raised by catastrophically polluting military programmes (e.g. Star Wars) which propose the physical destruction of orbiting objects, a process which could trigger an exponential rise in the amount of space debris as fragments collide with other fragments or working satellites. Also, proposals to erect "Space Art" (Malina, 1991) are particularly worrying for astronomers since these, by their nature, aim to reflect the maximum quantity of sunlight towards their earth-bound audience (Murdin, 1988, Malina, 1991).

As the subject for an International Science Symposium project (Junior Science and Humanities Symposium), we have investigated one aspect of the pollution caused by earth satellites – both currently working and "dead" objects in orbit. That is the effect of reflected sunlight from artifical satellites on astronomical observations (see Fig. 1).

For a summer project in 1988 at the Royal Observatory Edinburgh, one of us (MB) counted the trails on approximately 1,000 IIIaJ and IIIaF UK Schmidt* plates (6° by 6° FOV) obtained during several sky survey programmes from 1974 over a fourteen-year period. The trails were categorized into groups of "bright", "medium" and "faint" (close to the plate limit) objects with a further category of "flashing" which covered the whole brightness range. Using the

* The 48-inch Schmidt Telescope at Siding Spring in New South Wales in Australia is now operated by the Anglo Australian Observatory.



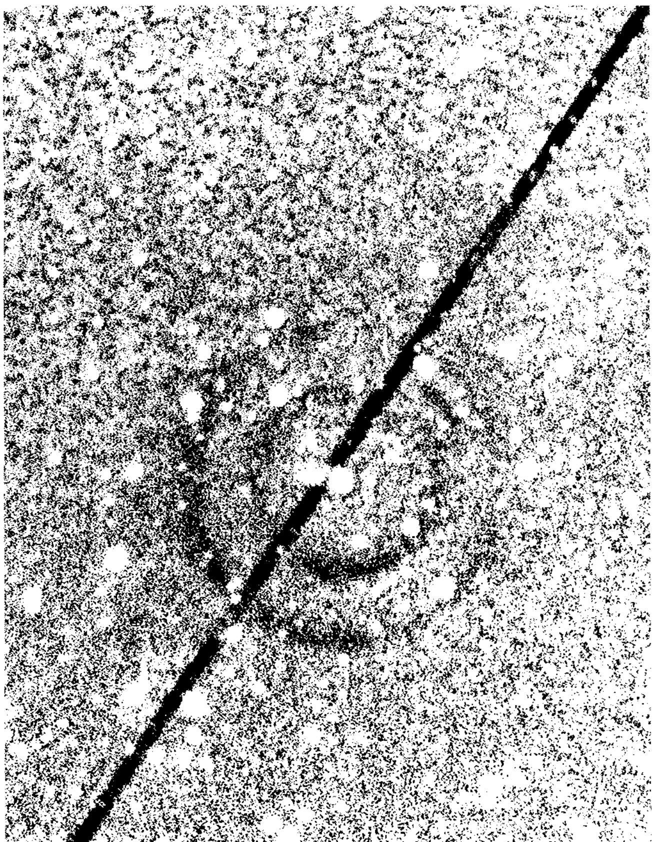
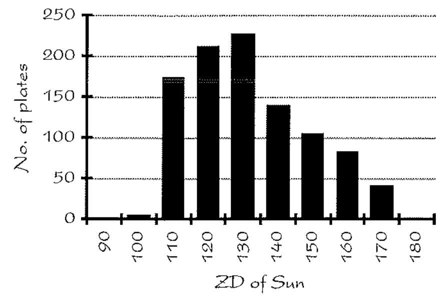


Figure 1: *(a) Five trails of differing brightness on UK Schmidt plate No. J14710 (Courtesy: David Malin, AAO).*
(b) The light echoes around the remnant of Supernova 1987A. A case where a trail has ruined an exposure (Courtesy: David Malin, AAO).



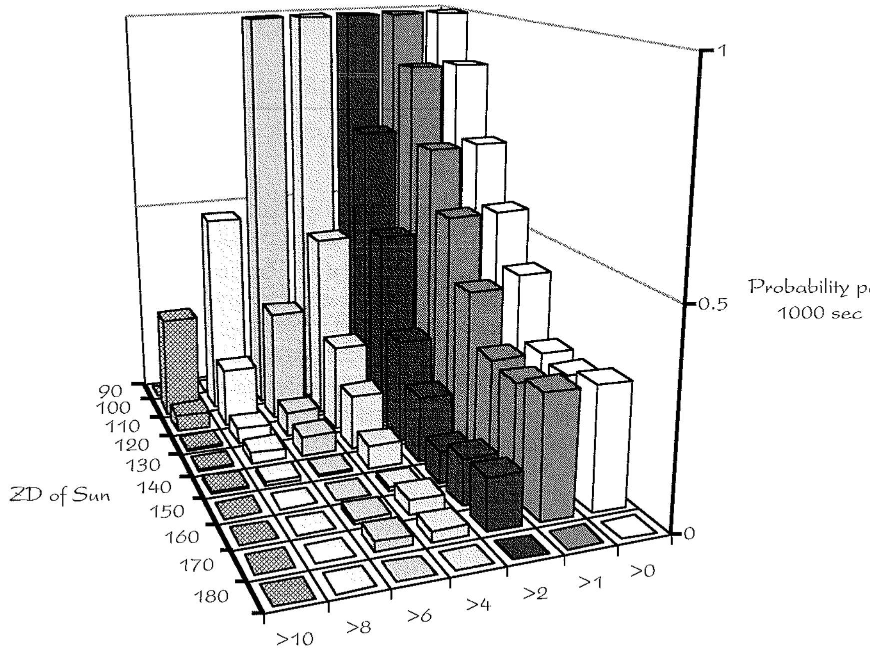


Figure 2: *The 2-D plot is the frequency distribution of the quantity of interest for all the plates. The 3-D plot shows the frequency distributions for alle the plates with > n trails per 1000-second exposure normalized by the unselected distribution – this gives the probability of finding at least this number of trails on a plate. The plot shows the distribution as a function of the zenith distance of the Sun. As expected, most trails are found near twilight – this is the time when even the low orbit satellites are still outside the shadow of the Earth.*

date and time of the plate, the exposure time and the plate centre, we constructed a catalogue containing the solar zenith distance, the angular separation of the sun and the plate centre and various other angles of use in describing the geometry of the Sun–Earth–Observatory–satellite system. The resulting table was defined as a "database" in a Macintosh "Excel" spreadsheet, simplifying the subsequent task of extracting multiply selected subsets.

Our primary method of visualizing the data was to construct normalized frequency distributions giving the probability of counting a given number of trails on a 1000-sec-exposure plate as a function of various angles. Figure 2 is an example which demonstrates the (expected) tendency to see most of the trails on plates taken during twilight ($ZD_{sun} \sim 100°$). This shows immediately the seriousness of the problem: essentially every plate taken close to twilight contains several trails.

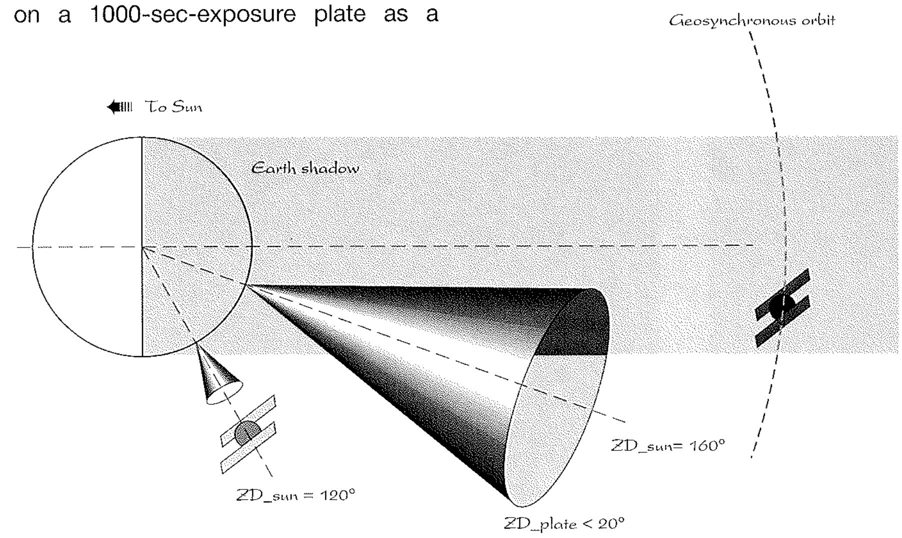
The relevant geometry can be understood from Figure 3 which shows how a satellite will enter the Earth's shadow at a Sun–Earth–satellite angle (θ) which depends on its orbital altitude. This suggests a method of making a statistical separation of the low Earth orbit (LEO) and the high and Geosynchronous satellites. It also allows us to determine the background contamination by (self-luminous) meteors which will be the only objects seen when looking along the Earth-shadow. Figure 4 shows the result of selecting only those plates with $\theta<120°$ or $130°$ – near twilight – and those with $\theta>150°$ – where only the higher objects will be seen outside the shadow. The latter suggests that the detected meteor flux is very low and does not significantly contaminate the measures of satellites. This is, presumably, because meteors – while they can have a high apparent brightness – generally move too fast across the field of view of the telescope to generate a significant exposure.

Given the fourteen-year time-base covered by the measured plates, we searched for evidence of a secular change in the probability of having plates affected by trails. This was done by computing the linear regression against calendar time of the number of trails per plate per 1000-sec exposure for (a) all the plates, (b) plates with $\theta<120°$ (LEO objects) and (c) those with $\theta>150°$ (high and Geostationary objects). In order to determine the error on the slope of the resulting regression lines, we took 30 repeated "bootstrap" samples from each of the selections and took the width of the resulting slope distribution functions to represent the uncertainty. The resulting slopes and their errors are:

(a) all plates, 0.190 ± 0.014 trails/1000-sec exposure plate/year

(b) $\theta<120°$, 0.299 ± 0.046

(c) $\theta>150°$, 0.115 ± 0.013



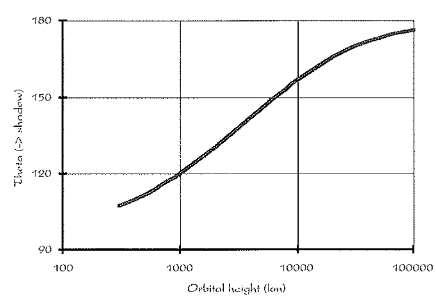


Figure 3: *(a) This drawing explains our ability to separate the populations of low- and high-orbiting objects using the angle between the Sun and the plate centre, θ (see text), as a discriminant. When looking down the Earth-shadow, only self-luminous objects (meteors) can be seen: we discover that these are very rare on the Schmidt plates.*
(b) The plot shows the angular separation of the Sun and the plate (at $ZD_{plate} = 0$) at which the satellite enters the Earth's shadow.

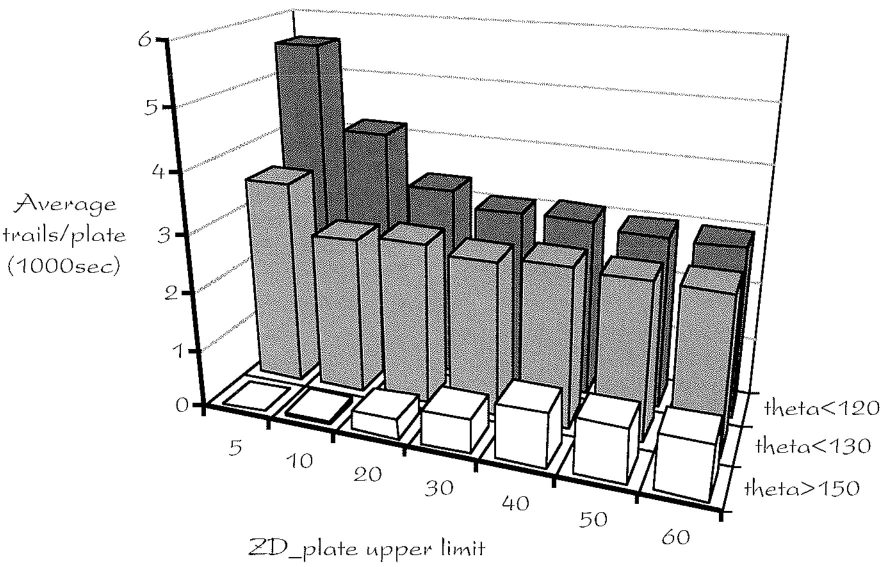


Figure 4: *This shows our use of geometry (the angular separation of the Sun and the plate) to separate the populations of low and high (probably mostly Geosynchronous) satellites. By looking at the average number of trails per plate with $\theta > 150°$ or $\theta < 120°$ and 130°, we see mostly high or low objects respectively. When the zenith distance is limited to lower values, the discrimination between these populations becomes sharper.*

This shows that the LEO objects are increasing the fastest while the high altitude objects show a slower, but still significant, rise.

Finally, we attempted to estimate the sizes of the objects which produced the trails of different strengths. This involved knowing the distance between the satellite and the observatory, the albedo and the "phase-angle" of the satellite and the orbital altitude – which determines the angular speed with which the satellite crosses the plate and hence the "effective exposure time." Figure 5 shows the choice of this effective time to be that taken for the image to travel a distance equal to a typical seeing disk (we assumed 1 arcsec). The two graphs show the apparent magnitude of a trail produced by objects of "radius" (we assumed a diffusing sphere with an albedo of 0.5) 20 cm and 4 m. These are the smallest objects we could expect to detect at LEO and Geosynchronous heights respectively. Note that the strength of a trail on a plate does not depend on the exposure time although, of course, the image of a star with which it is compared does.

In conclusion, we remark that, while in the early days of the ESO/SERC Southern Sky Survey project, "A"-grade plates could not contain a satellite trail, it is now virtually impossible to maintain this criterion. There is even one case (at least) of a trail being recorded on an exposure taken with the Wide Field Camera on the Hubble Space Telescope. This has a field of view some two million times smaller than that of a Schmidt plate! Astronomers should be aware of the necessity of the various space agencies and vehicle launching organizations to take a responsible

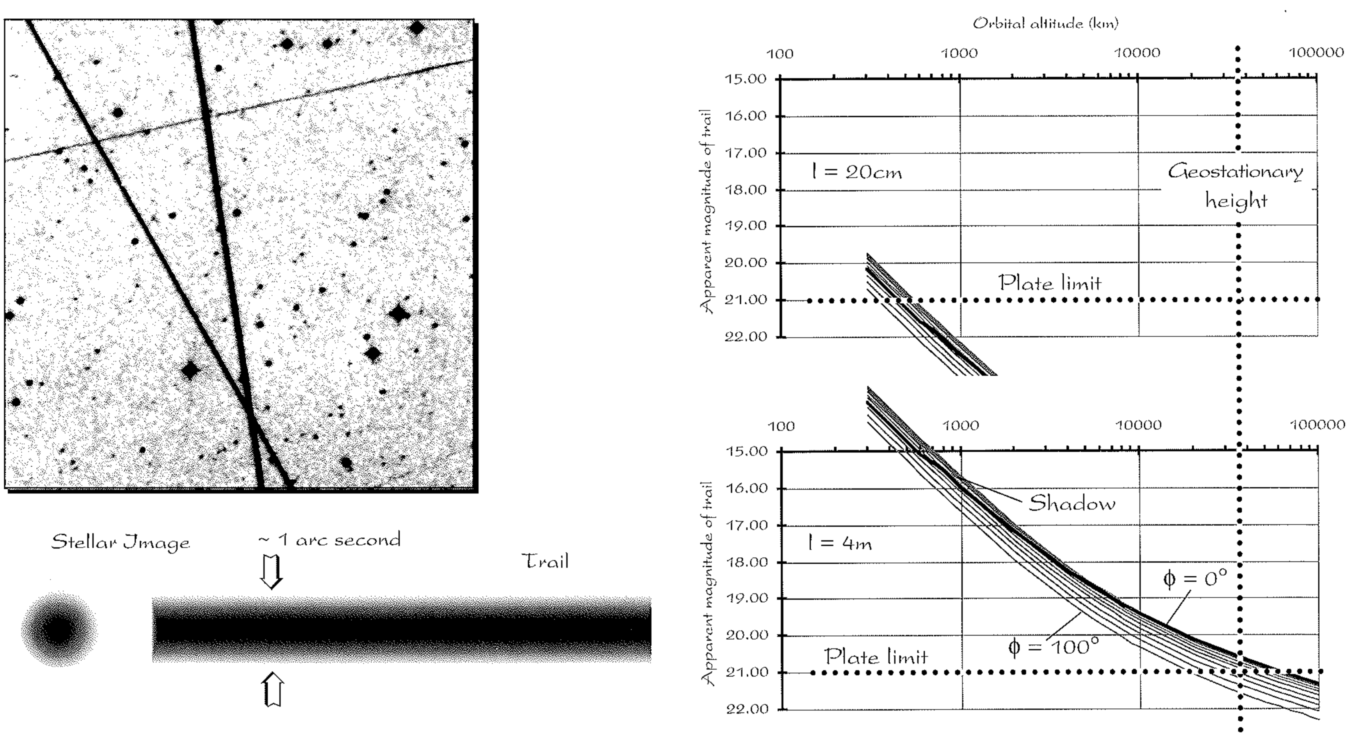


Figure 5: *(a) The appearance of a trail on a plate. Most of the satellites will appear so small to a ground-based telescope that they will be unresolved and so look like stars drawn out into a trail. The typical angular size of a stellar image on a plate is (at best) about an arcsecond. In our calculation of the apparent brightness of a trail, we compare the exposure of a satellite during the time it takes to cross its own diameter with that of a star (the exposure time of the plate). The strength of a trail as registered on a plate is therefore independent of the exposure time of the plate, unlike the stars with which the trail is compared.*
(b) Our calculation of the expected brightness of satellites as a function of altitude, phase angle (φ) and "size". We have adopted an albedo of 0.5 and show results for a (diffusing spherical) satellite of radius 20 cm and 4 m, limiting sizes to be seen at LEO and Geosynchronous altitude respectively.

attitude towards minimizing this source of pollution.

Acknowledgements

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Unidentified Object Over Chile

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During the night between January 23 and 24, 1992, a very uncommon object, in public terminology denoted as "Unidentified Flying Object (UFO)" passed over Chile. It was seen by thousands of people, from Villa O'Higgins (2100 km south of Santiago) to Copiapo (700 km north of Santiago and 200 km from La Silla).

Journalists of *El Mercurio* (the major Chilean newspaper) described the phenomenon as "a luminous cloud moving northward, from which suddenly grew a mushroom, like the one of an atomic explosion", and "similar to a spaceship with a tail, like the one of a comet"!

The object flew right over La Silla around local time 23^h20^m, and was seen by many of the observers and night assistants. The following description was compiled from the testimonies of several of them; all times are in the morning of January 24, 1992:

2^h15^m UT: (i.e. 23^h15^m local time): A small luminous ring with diameter about 0.5° is seen at west-south-west, 25 degrees over the horizon, moving slowly northward.

2^h15^m–2^h20^m UT: A small, sharp and bright object moves slowly, the ring expands to 5° in diameter, and a huge cone (40° long, 20° wide) follows the object.

2^h20^m–2^h21^m UT: it suddenly accelerates and moves rapidly to the west-north-west, 45° above the horizon. The main object becomes very bright (brighter than Venus!), remains sharp, and is surrounded by a small (1/4°–1/3°) ring (as seen with binoculars). It then becomes more and more diffuse and finally very quickly fades away.

Eric Aubourg, observer at the GPO (Brown Dwarf Experiment), had the good sense to take pictures of the phenomenon. The two exposures are shown in Figure 1 and 2. Even though we have until now no "official" confirma-

Figure 1: *10-second exposure around 23^h18^m (LT), on a TMax 400 film with a Leica camera, 35-mm lens, by E. Aubourg. This is an enlarged part of the negative. The object is seen, surrounded by the ring which is elongated by the motion during the exposure, and is followed by the cone.*

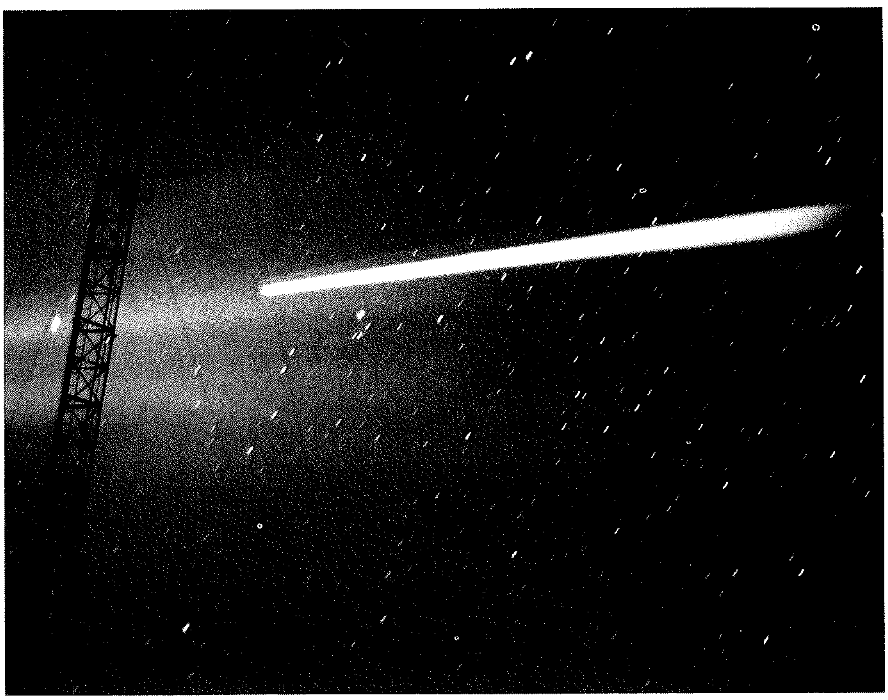

Figure 2: *1-minute exposure from 23^h20^m–21^m (LT) with the same technical parameters. This, however, is a print of the entire negative. To the left the remains of the cone are seen. To the right, the object is fading away and finally disappears.*