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Lightning and Triboelectric Charging Hazard Assessment for the Huygens Probe

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Lightning occurs in planetary atmospheres, and on Earth occasionally presents a danger to aircraft. The hazard to Huygens in Titan's atmosphere is assessed here. While data are extremely limited (there is no evidence whatever of lightning on Titan), it is possible to use physical arguments to make confident quantitative estimates of the hazard levels, and hence workable engineering specifications for lightning and other hazards. It is found that the risk of a lightning strike with an energy of 10^6 J or less is $<1\%$ during the Huygens descent. Protection against lightning strikes and charging is briefly discussed.

1. Introduction

Lightning is the sudden high-current discharge caused by the atmosphere's electrical breakdown. For it to occur, some kind of charge separation must first happen, usually created by convective processes involving droplets. Lightning can cause damage by the discharge's local heating and mechanical shock, and by the high electrical and magnetic fields from the current associated with the discharge.

The potential dangers of triboelectric charging (see later) and lightning were considered even during the early planning stages of the Huygens mission. An initial hazard assessment by the author (Lorenz, 1991) suggested that the hazard would be lower than that to terrestrial aircraft. Terrestrial lightning specifications (e.g. see Ponds, 1985) were thus imposed on Probe systems and experiments. The hazard was re-examined in 1993 in response to the potential difficulties and expense of meeting this specification. This re-analysis is summarised here.

2. Hazard Due to Natural Lightning

Lightning strikes on aircraft are not infrequent, but rarely prove to be catastrophic. US Army missile systems (Ponds, 1985) are required to survive *nearby* lightning strikes, but may not necessarily survive *direct* strikes.

Borucki (1985) and others indicate that commercial aircraft in the USA are struck once every 3000 h of flight. US military aircraft suffer rather less frequently because they spend less time in cloud, where about 80% of aircraft strikes occur (Clifford, 1980). A NASA Langley Research Centre F-106B aircraft flown through thunderstorms 421 times received 176 direct strikes and 54 near-misses, suggesting a strike probability in a thundercloud of about 40% (Borucki, 1985).

In order to assess the danger of flying through active thunderstorms, it is clearly necessary to estimate the number of such storms. As a first-order estimate, consider simply strikes per unit area. The most extreme case (Rinnert, 1985) is based on interpretation of radio emissions at Jupiter, and suggests a rate of up to $40/\text{km}^2$

annually. On Earth (and on Jupiter, if optical flashes rather than radio data are used), the figure is more like 10^{-3}/km^2/yr. Thus during the Huygens descent (~0.0002 yr) there is a maximum ~1% chance of a strike, with ~10^{-6} perhaps a more realistic probability.

The more rigorous approach that follows considers the specific physical limits on lightning activity on Titan.

Desch & Kaiser (1990) reported an upper limit on lightning activity set by the failure to detect any radio emissions during Voyager 1's flyby of Titan. They argue that any flashes during the flyby with energies of 10^6 J or greater (200-1000 times less than typical terrestrial lightning) would have been detected. The failure implies that either it is infrequent on Titan or occurs with very low energy. Although Grard (1992) proposed that a meteoric ionisation layer might have shielded lightning radio emissions from Voyager, no such layer was detected. Further, the low arrival velocity of meteors at Titan yields poor ionisation efficiency (English et al., 1996), so theoretical grounds for such a layer are modest.

Desch & Kaiser (1990) use a lightning dissipation rate given by Borucki et al. (1984) as $4 \times 10^{-6\pm1}$ W/m^2. This, in turn, was based on a value for convective energy flux of 1 W/m^2, or about 25% of the solar flux (Samuelson, 1983). Note that the solar flux referred to here is one-quarter of the solar constant S, as the solar constant must be averaged over the entire surface (day/night hemispheres) of Titan. However, more recent models of the radiative transfer in Titan's atmosphere (McKay et al., 1991) suggest that the fraction F of solar flux manifested as convective energy is only about 1%. Thus, for this hazard assessment, a convective flux value ($0.25SF$) of 0.04 W/m^2 is used, giving a lightning dissipation rate ($0.25SFR$) of $1.6 \times 10^{-7\pm1}$ W/m^2. The uncertainty derives from the variability in the fraction R (here ~4×10^{-6}) of convective energy dissipated as lightning, which varies by a factor of ~100 between Jupiter and Earth.

The probability of a lightning strike of energy 10^6 J occuring in any given square kilometre is therefore $1.6 \times 10^{-7\pm1}(10^3)^2/10^6 = 1.6 \times 10^{-7\pm1}$/s. Taking the Probe descent as 2 h (~10^4 s — a pessimistic value, as it will be in the troposphere for only about half of this time), we obtain a probability of being struck (or at least being in the same square kilometre as a 10^6 J strike) as about 0.001 (±an order of magnitude.) Strikes of higher energy are possible, but will occur with correspondingly lower probability. Borucki (1985) obtained a similar hazard level for the Galileo probe during its descent through Jupiter's cloud-laden atmosphere.

Thus the 1% hazard level obtained in the first estimate appears to be an extreme upper limit. Further, as the troposphere is ~40 km deep, the probability that Huygens is at the same altitude (±1 km) as a lightning strike is an order of magnitude lower than the figures above. In any case, this hazard level corresponds to a relatively weak strike, much weaker than terrestrial lightning.

Strike energy may be written as $0.5QV$, where Q is the charge on the cloud, and V is the cloud potential. V may be written as the product $V=E_bL$, where E_b is the breakdown field strength (typically 5×10^4 V/m but somewhat lower due to real-world physical effects rather than the laboratory breakdown value of dry air) and L is the strike distance (assumed 1 km). This gives about a 10 C charge for a typical terrestrial lightning strike of 2×10^8 J.

Breakdown field strength varies directly with pressure. As the pressure in Titan's troposphere is about the same as that on Earth, the same value of E_b seems appropriate. For a 10^6 J strike (if such a small strike can indeed occur) either the charge is lower, or the strike distance is less. If we consider a strike distance of ~100-500 m, we are left with a maximum charge of about 0.5 C, or about 1/20th that of the typical terrestrial strike. Golde (1977, p343) notes that a correlation exists between peak current and total charge, so we may expect the peak current to be smaller by a similar factor. As a result of this analysis, the peak current tolerance on Huygens equipment and experiments was relaxed from the terrestrial value of 20 kA (used in the initial Huygens specification: see Experiment Interface Document A, Issue 1 Rev. 0, December 1992) to 4 kA (EID A Issue 1 Rev. 2).

While there is no evidence of, nor strong theoretical arguments for, lightning on Titan (see Rinnert, 1985), current observational data cannot constrain lightning activity further than described above, so some small risk must be accepted. In principle, the available data do not rule out lightning strikes as strong as those on Earth (10^8 J or greater, with correspondingly high currents), but do assign extremely low probability ($<10^{-6}$ during the Huygens descent).

3. Probe-Induced Lightning

The previous arguments concern the 'obvious' case where the Probe flies into an area where lightning is already occurring. However, lightning strikes to aircraft can occur in clouds (and, on rare occasions, in the clear) where no lightning is previously observed (Clifford, 1980). This is termed 'Aircraft-Triggered Lightning', when the large conductive body of the aircraft intensifies an existing electrical field. This is especially so if the aircraft has large dimensions, as in an aircraft towing a gunnery target on a cable. Another example is the 110 m-long Apollo 12 launch vehicle, which was struck as it ascended through cloud above Cape Canaveral in November 1969. The effect is essentially the same as that of a lightning conductor: a potential difference over an air gap generates a certain electric field and if part of the air gap is 'shorted' by a conducting object, then the electric field (= potential difference divided by separation distance) is higher.

Consideration was given to making the parachute canopy and riser conductive to minimise the risk of triboelectric charging. However, such a canopy would have been extremely difficult to achieve technically, especially when considering the other challenges of parachute design for planetary missions (Scoon et al., 1989), and may have conflicted with the radio-transparency requirement (Lorenz, 1993a). Furthermore, a conductive riser would have increased the risk of aircraft-induced lightning. Thus the canopy and riser are made from (non-conductive) polyester and Kevlar, respectively.

Hazard assessment for Galileo noted that, although the bridle, riser and lines were non-conductive, they could have become covered with polar (i.e. conductive) aerosols or droplets from the clouds, such as H_2O, NH_3 and NH_4SH. Field intensification, as with terrestrial aircraft, could therefore have occurred.

On Titan, the expected atmospheric aerosols and droplets are of non-conductive hydrocarbons; polar compounds (H_2O, CO_2, HCN) are present only at part-per-million abundances, and are well below their freezing points. Thus, no conductive deposits are expected. As the Probe's maximum conductive dimension is only ~ 1 m, field intensification (and therefore Probe-induced lightning) can be neglected.

4. Triboelectric Charging

Triboelectric charging is the mechanism by which an aerospace vehicle becomes charged by flying through a cloud of charged droplets. The phenomenon became apparent to early aviators who suffered electric shocks when deplaning, until conductive skids became a common feature. Modern aircraft also carry small 'whiskers' on their wing trailing edges to dissipate charge build-up in flight.

For this phenomenon to cause a problem, two conditions must be met. First, charged droplets must be produced. Second, these droplets must transfer their charge to Huygens, by impaction.

If we assume that charged droplets exist (which may not be the case), we force the limiting factor to be impaction. Assume that kinetic energy of the impacting drop must equal or exceed the energy expended in overcoming the electrostatic repulsion between the charging Probe and the droplet. Then,

$$0.5mv^2 = Q_{Probe}q_{drop}/4\pi\epsilon r$$

If we take the Probe radius r as 0.5 m, and the drop (assume a sphere of diameter 9.5 mm, the largest size a raindrop on Titan can attain (Lorenz, 1993b), with a density of 500 kg/m^3) mass $m = 2\times10^{-4}$ kg and assume maximum relative velocity v (dominated by Probe terminal velocity under the parachute — raindrops fall at only ~2 m/s in Titan's atmosphere) in the troposphere of 10 m/s, then we obtain

$$Q_{Probe} = 5\times10^{-13}/q_{drop}$$

where q_{drop} is the charge on a single drop and charges are measured in C.

The number of large drops available is limited by the amount of methane in the atmosphere. If we take the extreme (indeed, absurdly so) of all the atmospheric methane (up to ~20% by mass of the atmosphere) condensing as drops, the column density is equal to the partial pressure of methane at the surface divided by gravity, or

$$0.20\times1.5\times10^5/1.35 \sim 2\times10^4 \text{ kg/m}^2$$

Thus the number of drops met by the Probe (area 1.3 m^2) is

$$1.3\times2\times10^4/2\times10^{-4} \qquad .3\times10^8$$

Hence, Q_{Probe} can be up to $1.3\times10^8 q_{drop}$. Combining these two conditions gives a maximum charge Q_{Probe} accumulated of about 8×10^{-3} C, corresponding to a charge per drop of 6×10^{-11} C. Since the impaction inertia scales directly with drop mass, and the number of drops for a given methane amount scales inversely, the charge build-up is independent of drop size.

It is instructive to compare the magnitude of this charge with that associated with, for example, a powerful camera flash, say $\sim5\times10^{-2}$ C. Since in any case this is much less than the charge associated with the lightning strike, the triboelectric charge hazard is lower than that due to natural lightning. Note also, in passing, that the maximum charge a droplet can hold is controlled by its surface tension and its dielectric constant. As these quantities are much smaller for methane than for water, the charge/drop of a given size is about one order of magnitude smaller for methane than water.

5. Conclusions and Protective Measures

In December 1978 the four Pioneer Venus probes were descending through the Venusian atmosphere when they suddenly suffered failure of all external sensors (temperature sensors and Net Flux Radiometers) at about 12 km altitude (Fimmel et al., 1983; Colin, 1980). This may have been from some kind of electrostatic effect, but it is not understood. The Nephelometer indicated the atmosphere at these levels was clear, so how could a charge be generated? Also, all four probes failed at about the same altitude, yet were separated by thousands of kilometres.

In the wake of the Pioneer Venus incident, the broadly similar Galileo probe was equipped with whiskers, to dissipate charge build-up, and Faraday cage shields on the external temperature sensors (Seiff, 1990).

On Huygens, standard spacecraft precautions against differential charging have been taken (minimum electrical conductivity requirements of surfaces, for example). Build-up of electrical charge, such as triboelectric charging, will be limited by incorporating three discharge rods (Fig. 1). In addition to preventing excessive charging, they form

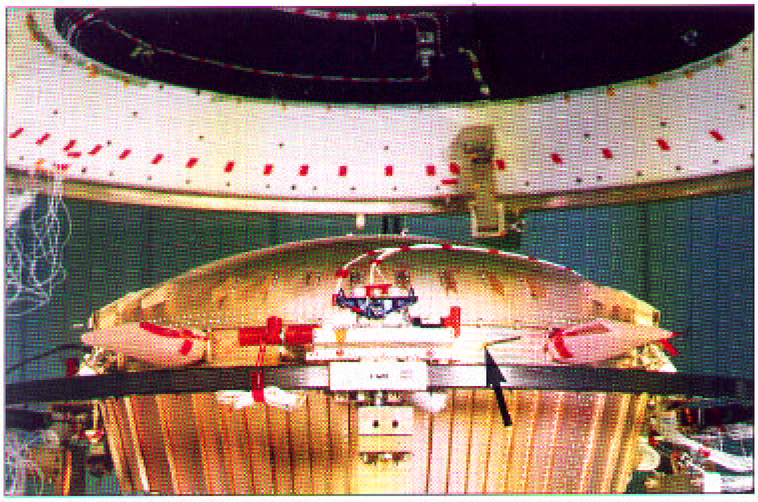

Fig. 1. Three lightning rods (one is shown arrowed), spaced at about 120° intervals, will limit charging and act as preferential points for lightning strikes.

preferential attachment points for ambient lightning strikes. Strikes on the rods are less likely to cause damage than strikes elsewhere. The lightning susceptibility testing programme is discussed by McCarthy et al. (1997).

In the (unlikely) event of a lightning strike, effects will be minimised by the Probe's outer shell, which acts as a Faraday cage. Additionally, there are requirements on rejection of common-mode induced voltages on harness wire pairs. The Faraday cage is essentially complete: even the Surface Science Package (SSP) 'top hat' cavity is covered over with a conductive mesh. Only a few areas, which require electrical contact with the exterior anyway, such as the radio antennae, radar altimeter and the Huygens Atmospheric Structure Instrument's Permittivity, Wave and Altimetry (HASI-PWA) package, are exposed.

The available evidence, and the arguments presented above, suggest that the hazard to Huygens due to lightning and charging effects is small. However, the solar system has surprised us before, so Huygens has been well protected before it ventures into the unknown.

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