An artificial meteor on Titan?

Ralph D Lorenz contemplates the astronomical observability of the entry of the Huygens Probe into the atmosphere of Titan – sound forensic astronomy and very good for public interest.

Abstract

The combination of ever-improving astronomical instrumentation and the peculiar aerothermochemistry of Titan's methane-rich nitrogen atmosphere may be such as to make it possible to detect directly from Earth the "meteor trail" created by the entry of the ESA Huygens probe into Titan in 2005. Such observations will be of enormous public interest, confirming the arrival of Huygens at its destination.

1: Fiery entry of the Huygens probe into Titan's orange haze-laden atmosphere, as visualized by artist James Garry (www.fastlight.demon.co.uk).

The entry of a space vehicle into a planetary atmosphere is violent and dramatic. In this paper I explore whether a particular event, the first ever entry (figure 1) into the thick nitrogen atmosphere of Saturn's moon Titan by the Huygens probe in early 2005, can be detected by astronomical observation. With measurements of adequate fidelity, scientific information on Titan's atmosphere might be gained as meteor emission can act as a probe of atmospheric physics and chemistry, but even a simple detection of the event is likely to be of significant public interest.

Furthermore, with the recent losses of Mars Climate Orbiter and Mars Polar Lander, space agencies attach considerable importance to verifying the safety and correct operation of space vehicles at each step of the mission. At the time of writing, the only positive information on the fate of the CONTOUR (Comet Nucleus Tour) spacecraft, with which contact was lost after the firing of its rocket motor to leave Earth orbit, was telescopic observation from the ground. Thus, "forensic astronomy" may be emphasized in coming years as a support to space missions, to aid in the identification and resolution of anomalies.

Astronomical instrumentation has improved dramatically in sensitivity and resolution in the last decade. Objects such as Titan, once only point-sources, are now resolvable into mottled discs by spaceborne telescopes and by the application of adaptive optics or speckle imaging techniques on the ground (see, for example, Lorenz and Mitton 2002). Sensitive detectors, large mirrors and narrowband wavelength isolation allow observation of even faint emissions from the planets, such as aurorae on Jupiter and Saturn (figure 2).

The question then arises of whether a spacecraft entry event can be detected. Of course, the massive entry explosions of the fragments of comet Shoemaker-Levy into Jupiter in 1994 were widely observed. More recently, impacts of only kilogramme-sized objects on to the surface of the Moon have been observed, even by amateur astronomers using small telescopes equipped with ordinary video cameras.

On signal strength terms alone, closer is better, but it should be noted that in terms of signal-to-noise, entries into more distant atmospheres are more readily observed (optically) than near ones. While the received power from the entry event decreases as the square of distance, the power reflected from the Sun decreases approximately as the fourth power (considering the terrestrial observer and the Sun as approximately coincident). The situation is analogous to radar jamming, which is successful at long ranges because of the same distance relationships. Thus, observing the optical emission from an entry at Mars or Venus may in fact be more challenging (requiring a much better radiometric resolution) than one of the outer planets.

Before considering the Huygens mission specifically, it is pertinent to recall an early entry event that was well documented.

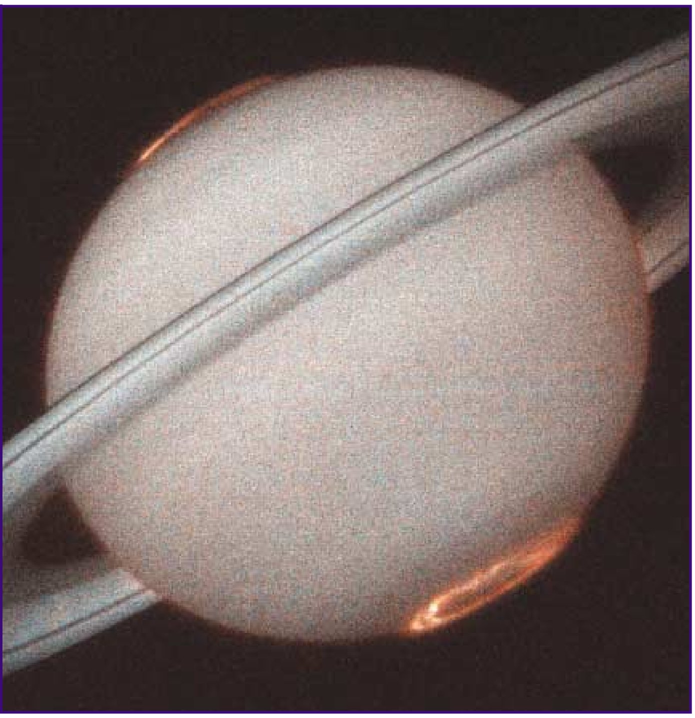
PAET observations of CN emission

The Planetary Atmospheric Entry Test (PAET – see Seiff 1973) experiment demonstrated many entry technologies and instruments, as a precursor to entry probes such as Viking, Pioneer Venus and Galileo. The small (62 kg) PAET capsule entered the Earth's atmosphere on 20 June 1971 at an entry angle of –41°, with a velocity of 6.6 $km\,s^{-1}$ – conditions not dissimilar from the entry of Huygens.

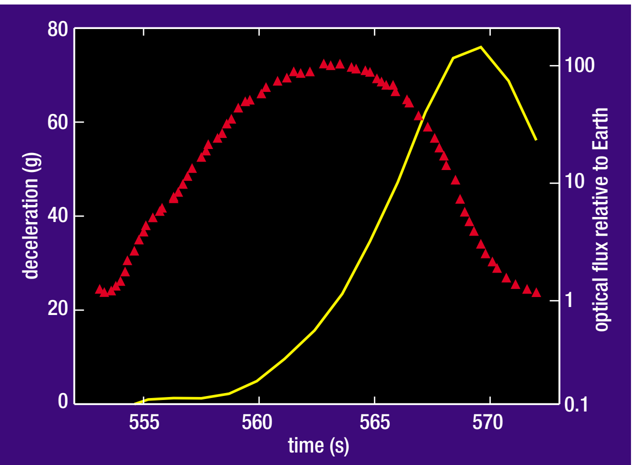
One instrument (Whiting *et al.* 1973) that PAET carried, which has not been used on other entry probes to date, is a stagnation point radiometer, designed to record the emission from the glowing shock-layer during entry. The relative brightness in several narrow wavebands, and the variation of brightness with time, are diagnostic of the atmospheric composition. The sensor comprised a set of photodiodes mounted behind a fixed aperture with interference filters to isolate narrow wavelength ranges. Although nine wavelengths were monitored, only the 387 nm "CN" channel and 391 nm "N" channel have been studied in detail.

During the entry the peak optical emission signal was around 100 times higher than the "albedo" signal, i.e. Sun reflected from the Earth (figure 3). At these short wavelengths, the Earth's atmosphere is quite bright owing to Rayleigh scattering.

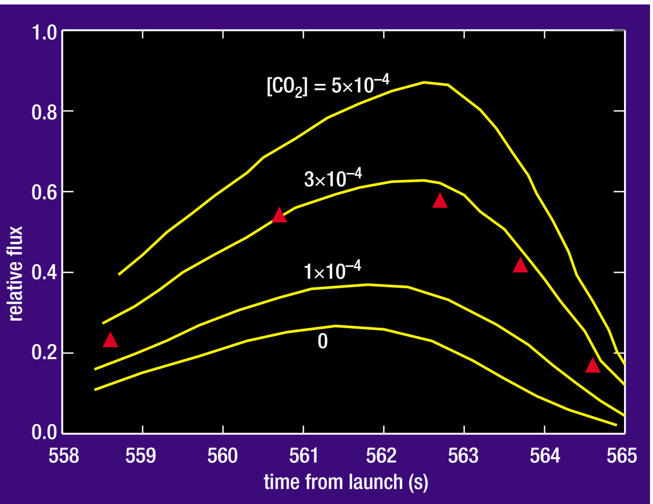
Simulations of the shock-layer radiation are complex. Not only must the radiative transfer problem be solved to evaluate the emission and absorption from different parts of the shock layer (at different temperatures), but the chemistry must also be modelled – in particular, the de-excitation that leads to the characteristic violet CN emission has a significant relaxation time. Models, validated by shock-tunnel testing, allow the interpretation of the optical emission data (figure 4), for example to recover correctly the carbon dioxide abundance in the Earth's atmosphere. The violet CN emission in



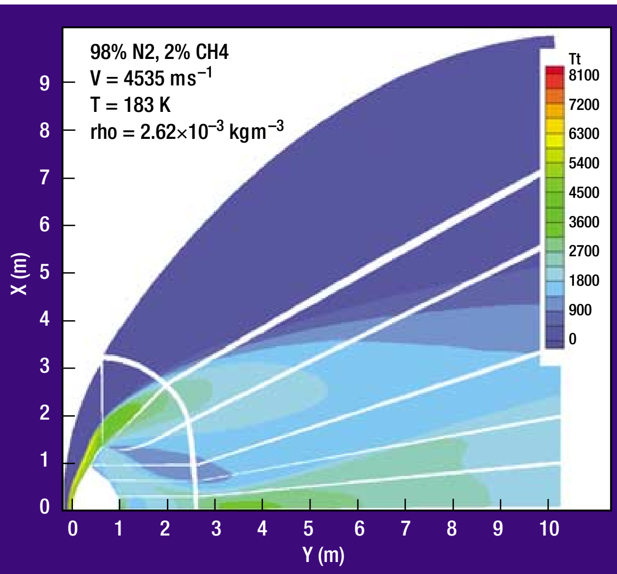
2: Modern instrumentation is able to detect faint optical emission from as far away as Saturn. The Space Telescope Imaging Spectrograph, used here to image aurorae on Saturn, would be an ideal instrument with which to detect the Huygens entry.



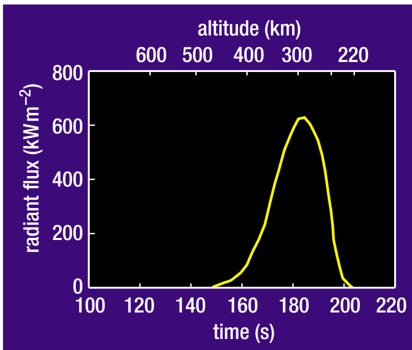
3: The nitrogen line emission (triangles) from the glowing shock layer during the PAET entry in 1971 peaked at around 100 times the brightness of the solar signal reflected by the Earth. Note that heating and optical emission depends on atmospheric density times the cube of velocity, whereas deceleration depends on density times the square of velocity, so peak deceleration (yellow curve) occurs later than the peak emission.



4: The CN line emission and its evolution with time is sensitive to the abundance of carbon atoms in the atmosphere. These data (triangles), recorded by the PAET radiometer, are fitted by a model (curves – see Whiting *et al.* 1973) with best fit corresponding to the known carbon dioxide abundance (~300 ppm). In this regime, emission has a nearly linear dependence on carbon abundance – this linearity will not extend to the very high levels of carbon in Titan's methane-rich atmosphere.



5: Sophisticated calculations of the flow field with coupled aerothermochemistry are used to predict the heat loads experienced by the heat shield. Note that these calculations (provided courtesy of Frank Mazoue of Atos Origin at ESTEC) showing the thermodynamic gas temperature in Kelvin indicate a large and warm wake, in addition to the hot shock-layer in front of the heat shield. Such calculations need to be extended further into the wake region to estimate correctly the observable emission from the probe.



6: The emission from the shock layer on to the front shield for the Huygens probe peaks at some 600 kW m^{-2}, or around 500 times the solar constant. The emission pulse lasts 20–30 s, during which the probe traverses the altitude range 400–250 km, above most of the atmospheric haze.

particular is very strongly sensitive to the abundance of carbon atoms.

Titan and Huygens

Titan is a relatively small body (between Mercury and Mars in size) with a remarkably thick (1.5 bar surface pressure) nitrogen atmosphere – making it the easiest atmosphere in the solar system into which to enter – and the atmosphere is vertically very extended (owing to the low gravity of 1.3 m s^{-2}) and so it is like a large, soft cushion, spreading the entry energy dissipation over a relatively long time.

But the chemical aspect of aerothermodynamics was of significant concern in the detailed design for the heat shield of the Huygens probe. Titan's atmosphere contains around 2% methane, the photolytic destruction of which leads to a host of organic compounds in its atmosphere, and the orange haze that obstructs optical sensing of the surface at short wavelengths. This large abundance of carbon atoms leads to a significant enhancement of the radiative heat flux on the shield compared with other atmospheres at the same dynamic conditions.

The Huygens probe (e.g. Hassan and Jones 1997), part of the joint NASA–ESA Cassini–Huygens mission, was launched in October 1997. After arrival at Saturn in summer 2004, the probe will be released from the Cassini Orbiter on 24 December 2004 and will coast in a dormant mode for 22 days to enter the atmosphere of Titan at around 6 km s^{-1} and make a 2.25-hour parachute descent to Titan's mysterious surface.

The entry angle is 65°, remarkably steep and permissible only because of the forgivingly large-scale height of Titan's atmosphere and the modest entry velocity. The probe crosses the entry interface (1270 km) at this angle, and continues on a more-or-less rectilinear trajectory which, because Titan is so small, has a progressively more and more shallow flight path angle. At the altitude of peak heating, around 400 km (well above the main haze layer at around 150 km), the radiative flux on the shield will be around 600 kW m^{-2}, or roughly 500 times the solar constant at Earth. There is also a similar level of convective heating, so after its long cold cruise in space Huygens has to endure – literally – the "heat of a thousand suns".

The front shield is protected by a material (AQ60) developed for French ballistic missile warheads. This material, a phenolic-impregnated silica felt, is similar to the material used on the Space Shuttle tiles. The back side of the probe (the rear face of the front shield, and the aft cover of the probe itself) are protected with a lighter (and cheaper) thermal protection system. The material used, Prosial, is a resin foam of silica bubbles. Its expense is considerably reduced because it can be sprayed onto the protected surfaces, while AQ60 must be carefully machined into tiles that can be precisely mounted on the front shield.

Energies

Peak deceleration occurs slightly after peak heating, at a modest level of 12 g. One can get a crude idea of the energetics involved by multiplying this figure by the probe mass of ~300 kg and its speed of ~4 km s^{-1} , yielding a loss rate of kinetic energy of ~150 MW. The front shield has an area of about 5 m^2, so the peak radiative flux of 600 kW m^{-2} corresponds to only ~3 MW of heating on the probe – the probe's survival, like that of most entry vehicles, relies on the strong shock produced by the blunt shape to ensure most of its energy is deposited into the atmosphere.

The 3 MW corresponds to a "luminous efficiency" of around 2%, which may be compared with the canonical value for terrestrial meteors of ~1% (e.g. Bronshten 1981). The efficiency is believed to increase with entry velocity (which is typically about four times higher for terrestrial meteors than for Huygens), so the Titan shock layer is rather a strong radiator, because of the CN radiation.

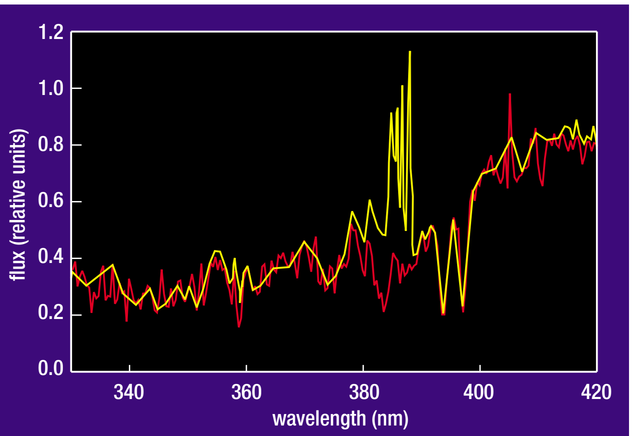
The 3 MW figure is the energy deposited on the 5 m^2 front shield – crudely one may expect a comparable area of the shock to be visible from Earth and we therefore use this figure as a baseline in the calculations that follow. However, as for meteors, there may be significant optical emission from the "trail" as chemistry continues to liberate energy in the wake (see figure 5). Calculations to date, devoted only to evaluating the heat loads on the front shield, have not integrated the total emission, which could therefore be a factor of several higher than the 3 MW figure above.

Recent studies of terrestrial meteors (Rossano 2000) have indicated that the radiant emission in the mid-infrared can exceed the optical emission by a factor of 25. It may be remembered that the most striking (i.e. high contrast) images of the impact of comet Shoemaker-Levy 9 with Jupiter were taken in the infrared. Thus the infrared flux from the wake may be some tens of megawatts.

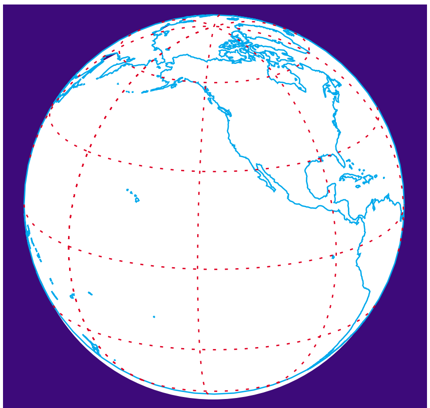
Astronomical observability

Studies of the aerothermochemistry of the Huygens entry (although with a less massive probe, and a 90° entry angle) by Nelson *et al.* (1991 – before the final design of the probe had converged) show that around 25% of the total heating of the probe was expressed as radiation. This is consistent with the Baillon and Taquin (1995) figures indicated above – although the peak radiative flux and convective flux are similar, the convective heating occurs over a longer interval so the integrated heating is higher. Of the radiative flux, about 41% was as CN violet and 59% as red light. Scaling from the discussion in the previous section, about 1.5 MW or more of CN line emission can be expected.

Titan's opposition flux at this wavelength is



7: The nonequilibrium CN radiation has a distinctive violet spectral signature with strong emission in several narrow lines. The emission (as measured in plasma wind tunnels – see Rôck *et al.* 1993) is shown superimposed on the Titan spectrum. For clarity, the example shown here assumes an unrealistic contrast of ~2, whereas 0.01–0.1 is more likely, although this is somewhat countered by the limited spectral resolution of the emission data used here.



8: Earth as viewed from Titan on 14 January 2005, at 09:00 UTC. The Sun is directly behind the Earth. Major continental US observatories and Hawaii are well placed to observe Titan, although Titan is just setting for the ESO facilities in Chile.

2×10^{-13} erg cm^{-2} Å^{-1} (Lockwood *et al.* 1986) and therefore averaged over a 10 nm wide filter the entry flux is only about 1 part in 10^5. This would indeed be challenging, even given recent improvements in photometry for transit detection of extrasolar planets. The duration of the heating event is approximately 30 seconds (figure 6) – a detection of the entry will therefore rely on obtaining adequate signal-to-noise in an integration period of that time or less. The relative flux improves to two parts in 10^4 if a narrowband filter is used to better isolate one of the emission lines.

The figures above consider Titan as a point source, however. The Wide-Field and Planetary Camera on HST resolves Titan into about 300 pixels, only one of which would be brightened by the entry flux. The relative photometry requirement therefore improves by that factor, becoming of the order of 1% (with a filter 1 nm wide), using even the pessimistic assumption of a 5 m^2 emission area. The Space Telescope Imaging Spectrograph – if the slit can be reliably positioned on the right part of Titan's disc – could do even better, since it would take a spectrum of Titan pixels containing the entry emission and adjacent ones without (see figure 6), with a spectral resolution of 0.3 nm, thus permitting high contrast from the narrow emission lines.

Adaptive optics (AO) systems have improved dramatically in recent years, although it is unlikely that they can be made to function adequately at the short CN wavelengths – they perform better in the infrared where the spatial scale of terrestrial atmospheric wavefront distortion (and thus the time constant within which the mirror deformation actuators must respond) is much larger. Since the infrared emission from the probe's wake may be quite large, however, AO observations may also have a high probability of detecting the entry. Taking a 20 MW figure for a 4 µm spectral bandwidth gives a contrast of around 3% per 0.1 arcsec pixel when compared with Titan's emission flux at 4.6 µm of 4×10^{-15} W m^{-2} µm^{-1} (Noll and Knacke 1993).

Following the probe mission redesign last year to correct a problem in the radio receiver, the probe is due to cross the 1270 km entry interface at around 09:00 hours UT on 14 January 2005. At that hour of the day, it will be well into the night over both Hawaii and the Western USA, sites of many prominent and capable observatories with 10 m telescopes such as Keck and the MMT (figure 8). The viewing geometry is in fact rather similar to that which pertained during an occultation in December 2001 of a double star by Titan, an event that was documented by a breathtaking AO movie in the near-infrared, obtained by Antonin Bouchez and colleagues using the 200-inch Palomar telescope and a number of other observations from Hawaii and Arizona.

Conclusions

This paper has outlined calculations that show promise for the detectability of the Huygens entry. With modestly pessimistic assumptions, the event is marginally detectable at optical wavelengths. However, this is far from being a well-understood problem and the emitted flux may be considerably underestimated since existing aerothermochemical and aerothermodynamic calculations do not evaluate the glow from the deep tail. Further analyses are urged with the revised probe mission parameters to understand this better.

Additionally, the partitioning of entry energy into thermal infrared flux is presently not well understood, but recent observations of meteors indicate that the thermal "luminous efficiency" may be considerably higher than the optical value. The sensitivity and resolution of new telescopes in the 8–10 m class at near- and mid-infrared wavelengths may mean that these facilities, many of which will be well placed to view the entry in 2005, will have the best chance of detecting the event.

It is hoped that many observations of Titan will be made contemporaneously with the probe entry in any case, to put the probe measurements in a context of spatial and temporal-variability (exactly simultaneous observations by the Cassini orbiter are impossible owing to operational safety constraints and the orthogonal mounting of the high-gain antenna and optical remote-sensing instruments). The possible detection of the probe entry itself is a prospect that makes these observations all the more important and exciting and might offer insight into meteor science as well as Titan's atmosphere.●

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